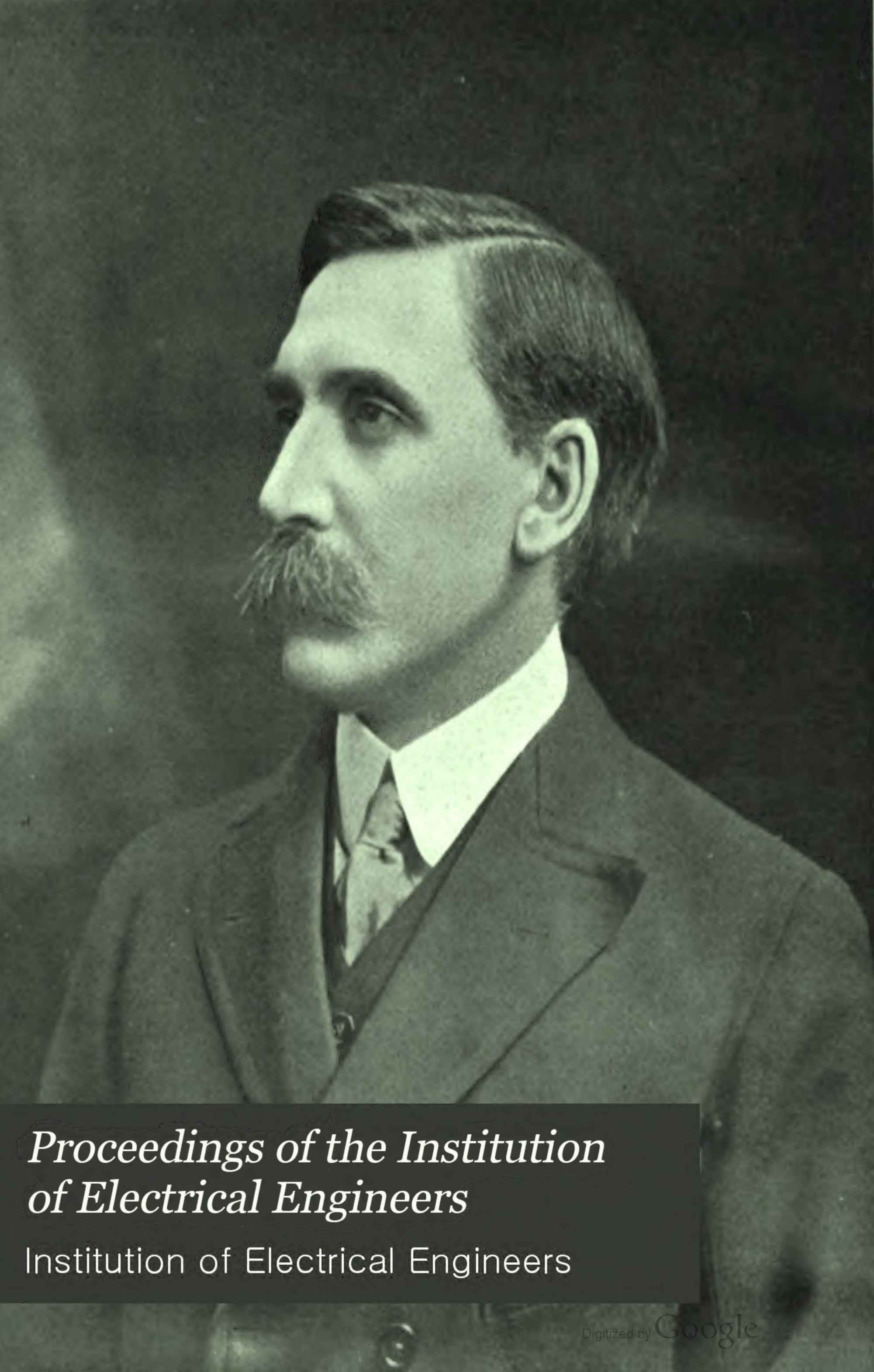

JOURNAL

OF THE

INSTITUTION OF

ELECTRICAL ENGINEERS,

ORIGINALLY

THE SOCIETY OF TELEGRAPH ENGINEERS.

FOUNDED 1871. INCORPORATED 1883

EDITED BY P. F. ROWELL, SECRETARY.

VOL. 46. 1911.

E. AND F. N. SPON, LIMITED, 57, HAYMARKET, LONDON, S.W.

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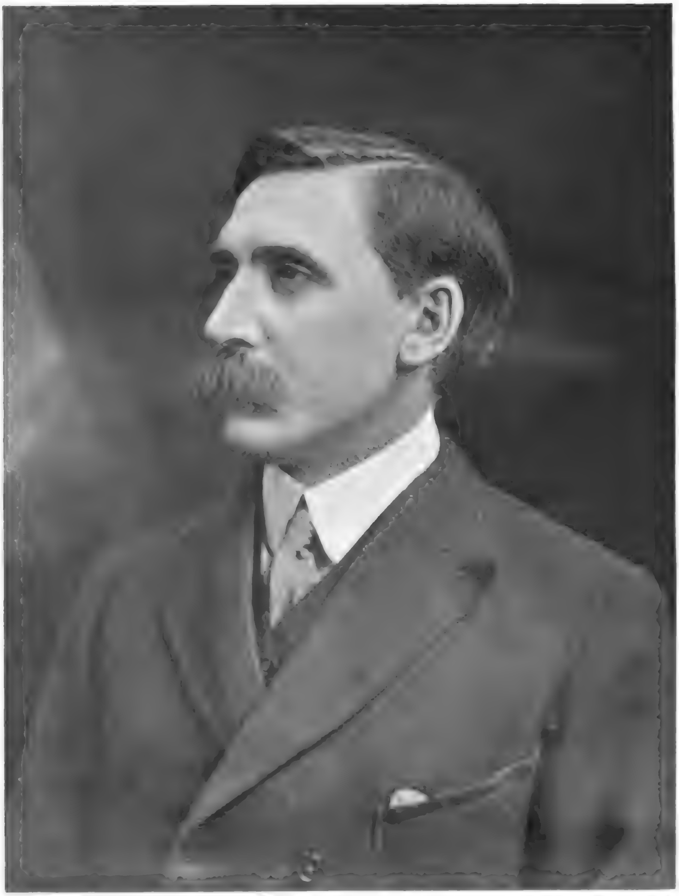
1911.

The Institution is not, as a body, responsible for the opinions expressed by individual authors or speakers.

TABLE OF CONTENTS.

VOL. 46.



S. Z. de Ferranti

PRESIDENT 1910-11

The Institution of Electrical Engineers.

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JOURNAL

OF

The Institution of Electrical Engineers.

Founded 1871. *Incorporated* 1883.

VOL. 46. 1911. NO. 205.

Proceedings of the Five Hundred and Tenth Ordinary General Meeting of the Institution of Electrical Engineers, held on Thursday, November 10, 1910—Dr. GISBERT KAPP, President, in the chair.

The PRESIDENT: Ladies and Gentlemen,—To-night is an historic occasion; it is the first time that our Institution meets in its own home. The Council hope to celebrate that great change in a fitting manner at a later date, but meanwhile they offer you a hearty welcome on your first appearance in your own house.

For thirty-eight years we have enjoyed the hospitality of the Institution of Civil Engineers, but the growing importance of our profession and our growing membership have made it necessary to acquire these premises. Probably you will not find in all London a better site for a scientific Institution than the one which we have been fortunate enough to secure, and the Council trust you will also find the structural alterations which had to be made to adapt this building for our purposes perfectly satisfactory. If we feel at home here, as we all hope we shall do, we should not forget that we have been indebted for a long time to the hospitality of the Institution of Civil Engineers, and I think we cannot begin our proceedings to-night in a better way than by passing, which I ask you now to do by acclamation, a hearty vote of thanks to the Institution of Civil Engineers for their long-continued hospitality.

The resolution was carried by acclamation.

The minutes of the Annual General Meeting, held on May 26, 1910, were taken as read, and confirmed.

The list of candidates for election into the Institution was taken as read, and it was ordered that it should be suspended in the Library.

The following list of transfers was announced as having been approved by the Council :—

TRANSFERS.

From the class of Associate Members to that of Members—

Sydney Edward T. Ewing.
Harold A. McGuffie.
William Tatlow.
Arthur Kepple Taylor.
John Charles A. Ward.

From the class of Associates to that of Associate Members—

Edward Alan Christian.
William A. Fitzgerald.
Henry Herbert Pickford.
Thomas Reginald Stancombe.

From the class of Students to that of Associate Members—

Charles Edmund Abell.
Ernest Adamson.
Frederick Wm. Geoghegan.
George Harlow.
John Marshall.
John Wm. G. Meaby.
Stanley Melbourne Mohr.
Edward Gerald G. Thompson.
Hugh C. C. Tufnell.

Donations to the *Library* were announced as having been received since the last meeting from E. Bennis & Co., Ltd., The Board of Education, Dr. C. Chree, T. H. Churton, The Commission of Conservation, Canada, W. R. Cooper, N. R. Corke, W. Cramp, J. T. Dixon, Dr. C. V. Drysdale, W. Duane, J. Eck, The Engineering Standards Committee, A. Garbasso, T. Hart, Dr. A. Hay, H.M. Patent Office, H. M. Hobart, G. W. O. Howe, E. P. Hyde, A. H. Jackson, Professor T. Mather, R. B. Matthews, W. P. Maycock, The National Physical Laboratory, F. E. Nipher, Major W. A. J. O'Meara, C.M.G., W. H. Patchell, G. Quincke, E. Raymond-Barker, The Silent Electric Clock Company, Technische Hochschule zu Danzig, Professor W. C. Unwin, L. H. Walter, and Dr. H. Wilde ; to the *Building Fund* from Major W. A. J. O'Meara, C.M.G. ; and to the *Benevolent Fund* from J. F. Avila, The Electrical Engineers' Ball Committee, The L.C.C. Electrical Staff Dinner, W. Routledge, J. H. Tonge, and The "25 Club," to whom the thanks of the meeting were duly accorded.

The PRESIDENT : I shall now call on Colonel Crompton to make a few remarks on the work of the International Electrotechnical Commission.

Colonel R. E. B. CROMPTON, C.B.: It may not be known to the members present here to-night that almost the first use to which this building was put after it had been acquired by the Institution was to hold in it the first meeting in England of the International Electrotechnical Commission. That meeting was held in the small original theatre that occupied this identical site. Mr. Arthur J. Balfour was then in the chair and addressed the assembled delegates. During the time that has elapsed since, the question of the international interchange of electrical ideas had gone on apace, and now sixteen leading countries of the world have joined, and have formed their own committees to co-operate with the other national committees. As you know, the Institution of Electrical Engineers of England from the very first took a leading part in the question, and, as I have already said, the first Congress was held here in this building. The second meeting, which was of the nature of a rehearsal for the full meeting which is to be held at Turin next year, was held for the first time in another country, in Brussels last August, and I have been asked to say a few words to you to-night as to what there took place. It will be best, perhaps, to put it in the words of the President of the International Commission, Elihu Thomson, the well-known American scientific man, and one of the greatest men of the time, at all events in our electrical world. In acknowledging the receipt of the Reports of the Conference, Elihu Thomson said that "no work of such huge importance to the electrical industry has exceeded that of the work commenced during the last few years in the international exchange of electrical ideas. It is a very difficult thing to carry on these matters internationally; there are many jealousies to be overcome, many susceptibilities to be met; and it is something to be proud of that no quarrels and no troubles have yet arisen."

We now seem to be in a fair way towards obtaining what we desire, that is, a practical international language of electricity, *i.e.*, that an engineer in any country may be able to express himself in such electrical terms as to be understood without risk of error by the electrical engineers of other countries. This is the first object. Our second object is to some extent to standardise machinery, so that its output and nature can be understood equally all over the world. This is what in England and America is called Rating. And, finally, we have boldly attacked the great question of standardising the symbols used for mathematical expressions. This is a very great work indeed, which affects so many other branches of engineering science that we electrical people were somewhat bold to tackle it. But we have tackled it, and we have already made considerable advance, and I think it augurs well for the future that in the short time we have been at work we have made some substantial advance. I think it is something to be proud of, and for this we have much to thank the labours of the Committee of the British Institution of Electrical Engineers. To their labours, and to those of the French nation alongside us, the general international advance is greatly due,

and I think probably that this is the reason why I was asked to speak this evening, for it is a matter which we English electrical men may justly be proud of.

The President (Dr. G. Kapp) then presented the premiums and scholarships referred to in the Annual Report for the year 1909–10.

The PRESIDENT: I now call on Mr. Ferranti to take my place and to read his Inaugural Address. Mr. Ferranti, I am sure, needs no introduction to you.

The chair was then vacated by Dr. Kapp, and taken by the new President, Mr. S. Z. de Ferranti.

Colonel R. E. B. CROMPTON, C.B.: It is with the keenest pleasure that I fulfil the duty of proposing a vote of thanks to the retiring President, as I probably have the longer electrical acquaintance with Dr. Kapp. Dr. Kapp came to me when he was not an electrical engineer, and you know what he has now become. During the long years that we worked together I had the fullest opportunity of seeing what lay in Dr. Kapp and what a brilliant future he was likely to have. We know how he has realised our expectations not only here, but also in Germany. I think that the Institution was to be congratulated in securing as our President a man who had one complete electrical training in this country and another complete electrical training in Germany, and who has then come back to us again. We must all feel proud that the attractions of our country brought Dr. Kapp back to us. Our Council knows how valuable and unremitting has been his work during his year of office. Those who have not filled the Presidential chair do not know the anxieties and the heavy work entailed on the President of the year; Mr. Ferranti has it yet before him. Dr. Kapp has in every way filled the chair to the satisfaction of every one who came in contact with him, and the Institution cannot fail to be benefited thereby. It is very difficult to say what one would like to say on a resolution of this kind, but I feel very strongly myself that we ought to congratulate ourselves on our retiring President having been such an ornament to our profession and such an ornament to this Institution of which he was the head.

Mr. W. M. MORDEY: I need hardly say that it gives me the very keenest pleasure to second the proposal that has been put before you by Colonel Crompton. I felt great gratification when Dr. Kapp was selected as my successor. I felt that the Council had wisely honoured a man who by thirty years of strenuous work in electrical engineering, had done so much to advance the science and the industry in which we are all interested. It was my duty a year ago to welcome him as the coming President; I now heartily speed him as the parting President and wish him health and success, and, what I know he will value more than anything else, the strength and energy to continue the useful work in which he has so long been engaged and which has earned him the honour that you conferred on him. I have very great pleasure in seconding the proposal.

The resolution was then put and carried by acclamation.

Dr. GISBERT KAPP: Mr. President, Colonel Crompton, Mr. Mordey, and Gentlemen,—I rise to thank you all most heartily for the very kind way in which you have passed this vote by acclamation. It was peculiarly gratifying to me that Colonel Crompton should have moved and my old friend Mr. Mordey should have seconded this vote. I remember very well when I first met Colonel Crompton and he offered to give me employment at his works in Chelmsford. I was delighted at the idea, but had some misgivings as I had no practical experience in this particular branch of engineering. I told this to Colonel Crompton, and his answer was, "Never mind, come along, I will teach you," and he did so. Then Mr. Mordey and many of the gentlemen here have taught me; in fact, we all teach each other and help each other, and that is, I believe, the explanation of the feeling of good-fellowship amongst us.

The PRESIDENT then delivered the following Presidential Address:—

INAUGURAL ADDRESS.

By S. Z. de Ferranti, President.

I propose to address you on the following subjects :—

Coal Conservation,
Home Grown Food, and
The Better Utilisation of Our Labour.

I believe that these problems are closely connected and are all capable in a great measure of being solved by means of an electrical treatment.

There are few subjects more important to the people of this country than the question of the rapid and ever-growing rate at which we are using up our coal supplies. Many writers have dealt with this subject, and have suggested various remedies.

It may be said that the rate at which we can use coal is a measure of our industrial activity and prosperity. This would be true, perhaps, if we were using our coal without waste, or at least with reasonable economy, but it is certainly not true of what we are at present doing.

Taking all the uses for coal into consideration, I believe that we are getting back an amount represented by useful work of one kind or another of much less than 10 per cent. of the energy in the coal. We can never, of course, hope to get anything like the full value of the energy in the coal, but, on the other hand, throwing away more than 90 per cent. of the value of our coal in the process of conversion is of the greatest possible concern to the country. Moreover, there is a further waste involved in our present methods of using coal which is only second in importance to the one I have spoken of.

We now dissipate nearly the whole of the valuable by-products contained in the coal, consisting principally of fixed nitrogen.

Besides the question of the waste of our coal by misuse, there is another cause working at an ever-increasing rate towards the exhaustion of our supplies. I refer to the immense exportation of our coal to other countries.

I will now turn to the question of our food supplies, and without going into details, which are available for every one to read and study, I would remind you that we now import the greater portion of our food because we believe it pays us better to do so.

This state of affairs is brought about by a number of complex circumstances, but is, in a measure, due to the necessary uncertainty of prices in our market under our present system, the comparatively small acreage that we have available, and to getting an insufficient return from the land that we have under cultivation.

Our only chance, however, of supplying our food requirements lies in a successful system of intensive cultivation throughout the country. This, in its turn, depends upon many things, but primarily it can be stated that it involves spending money in order to get the greater return required, and our farmers are naturally averse to spending money when the return to be obtained is so problematical. It is also attributable to the fact of intensive cultivation requiring a liberal supply of chemical fertiliser for the land, principally in the form of fixed nitrogen. This commodity, on account of the wasteful system of using our coal, is, I believe, at too high a price to make intensive cultivation attractive to the farmer.

There is a further difficulty still standing in the way, viz., the want of knowledge on the subject of intensive cultivation, but I am sure that once a sufficiently general interest was felt in the country, and a sufficient prospect of reward to workers on this subject assured, that knowledge would grow at a rapid rate and soon bring about an efficient system of using our land to the best advantage.

The third subject that I have mentioned to you is that of our wasted labour. It may be said that all labour is useful insomuch as, if it were not required it would not be used. On the other hand, we may consider the theoretical case of all labour being wasted insomuch as it is possible to conceive of a vast automatic machine which, with the direction of a single person, would fill all our possible requirements and would include in its many functions a capacity for keeping itself in repair, and extending its operations to all new wants that it had to fill. There is, however, as in most things, the middle course for which we should aim, and that is, the supply of all our reasonable wants with the least possible amount of labour.

Looking at the question more in detail, we can first consider the labour spent in and about raising and distributing the coal which we now use, and which we would save under more economical conditions. Then there is the vast army of workers who are employed in cleaning up the dirt that is produced by our present methods of using coal. If we consider what goes on in every household we shall see how large a proportion of the domestic labour is devoted to this. There are also all the people who are now employed in the process of burning coal for all the various uses to which it is put and who represent an enormous amount of labour which, under a more efficient system, could be turned to better account in the interests of the country.

It must be evident that the more efficient running of the country as a whole, the more rapidly must it add to its wealth and diminish the amount of labour which individuals have to expend in order to live at a

given standard. This efficient working of the country to a large extent depends upon the proper use of its natural resources in the form of material and labour, and the saving of all waste in both of these which can possibly be brought about.

Considering the question of coal saving, by-product recovery, and labour saving, it is evident that the only way of obtaining material improvement under these heads is to concentrate the process of transformation of the coal and to carry out this process at the smallest reasonable number of centres.

It is in the process of transformation of coal into work in the form of heat and power that the great loss occurs, as this is always a most difficult process and requires the highest scientific and practical skill to carry out with even very moderate economy.

It has been proposed, with a view to accomplishing the above ends, to treat the coal at central stations and turn it into gas and distribute the energy in this form, but this process only goes a small way towards a solution of the problem, as under it, combustion—which is such a difficult problem—would be taking place at numerous points over the whole country, all tending to inefficiency, and the conversion of the gas into power is by no means easy, involving running machinery of the reciprocating class, requiring special and skilled attendance.

It appears that with a problem such as we are discussing it is fundamental that the energy in the coal should be converted at as few centres as possible into a form in which it is most generally applicable to all purposes without exception, and in which it is most easily applied to all our wants, and is, at the same time, in a form in which it is most difficult to waste or use improperly.

We are therefore forced to the conclusion that the only complete and final solution of the question is to be obtained by the conversion of the whole of the coal which we use for heat and power into electricity, and the recovery of its by-products at a comparatively small number of great electricity producing stations. All our wants in the way of light, power, heat, and chemical action would then be met by a supply of electricity distributed all over the country.

It must, however, be remembered that the distribution of energy in the form of electricity instead of coal can only be effectively carried out when it can be done in such a way that it is available for all the purposes for which coal is now used, and this can only be the case when the conversion is effected at such an efficiency as will cause the electric energy delivered to represent a high percentage of the energy in the coal. Failing this no scheme for conversion at the pit's mouth and delivery of energy in the form of electricity is sound. There is also another controlling factor which must be satisfied in order to make this scheme possible. Both the conversion of the coal into electricity and the distribution of the current must be effected at a low capital cost so as not to overburden the undertaking with capital charges.

Considering the various processes of conversion which are now available, or which may be invented, and their possible and probable

efficiency, we first come to electric generators driven by reciprocating steam engines. Their economy, expressed in the form of energy in the coal to electric energy, may be taken as a maximum of 10 to 12 per cent. This is, of course, far too low an efficiency to make any scheme such as I have already indicated possible, besides which the capital expenditure and the complication involved are far too great and the size of the units too small to be thought of for the purpose in view.

We next come to large steam turbines such as have been constructed up to the present, and see that their maximum efficiency may be put down at about 17 to 18 per cent.

Next in the list, in order of economy, comes the big gas engine fed from gas producers, with an efficiency of coal energy to electric energy of possibly 25 per cent.

In the future we have to look towards two other means of conversion—the gas-turbine-driven electric generator and the production of electricity in some more direct way from the coal, but these two means of conversion, although capable of giving the most efficient results, are so much in the distance, that they are quite beyond our present consideration.

After very careful thought on the subject I have come to the conclusion that, in order to supply electricity for all purposes it would be necessary, amongst other things, to have a conversion efficiency of not less than 25 per cent.

For the purpose of looking into this question I have taken the figures of production and consumption given in the Report of the Royal Commission on Coal, which clearly summarises the position as it stood a few years ago, and as the increase taking place is fairly regular these figures have been taken throughout. According to this report 167 million tons of coal were being used in the country in 1903. Of this amount 2 million tons went to coasting steamers and 15 million tons were used by the gas companies. In order to simplify matters, and make the figures clear, I have left out of consideration the coal used on these two items, and taken the balance —viz., 150 million tons—as the annual coal consumption of the country. If now, instead of using this coal for doing work as at present, we were to convert it into electricity, we should use, instead of 150 million tons, 60 million tons of coal a year. This coal, turned into electricity, would produce 131,400 million Board of Trade units, and the electricity so produced would, after allowing for losses of transmission and conversion into work of different kinds, be sufficient to supply the whole of our requirements now being satisfied by the use of the 150 million tons of coal which we now burn. To form an idea of the magnitude of the proposal it is well to compare it with electrical supply as we know it to-day.

At present of all the coal we burn in the country only 1 per cent. is used by the public electric supply works of which returns are published, and it is therefore evident that electricity has up till now hardly commenced to displace direct-used coal.

In the conversion of coal into electricity one of the most important considerations is the load factor at which the converting and distributing plant effects the operation.

Electricity used for lighting, cooking, power, and traction must be supplied as and when required. On the other hand, domestic heating will be done largely through the medium of heat storage, and is therefore a controllable form of demand. Metallurgical and chemical processes, which depend for their success upon a very cheap supply of current, will have to be so adapted and modified that they can take current intermittently and so fill up the load curve, thus enabling the current which they require to be produced with the least capital expenditure and at the same time greatly assisting the good conversion efficiency of the whole supply. I believe that under the circumstances a load factor of 60 per cent. would be obtained. At first sight it seems unreasonable to expect such a load factor, but it must be remembered that our ideas are based on the present electric supply, which only uses some 1 per cent. of the coal now consumed in the country.

At present, as is quite natural, electricity is used for what coal does least satisfactorily direct, and it is misleading to compare the load factors so obtained with those which will be got when electricity replaces coal entirely.

Considering now the means to be adopted for converting the coal into electricity, and the efficiency at which this can be done, we find that in gas-engine-driven alternators we have a system theoretically capable of returning 25 per cent. of the energy in the coal in the form of electricity, and from this point of view they would meet our requirements.

The gas engine, however, as a converter of energy on the scale required suffers from the fact that the units are too small and the cost of the complete installation is too high. These difficulties appear to defer the realisation of an all-electric scheme until electricity is generated by some gas turbine of the future, or direct from coal by chemical action.

There is, however, an intermediate process of conversion which will, I believe, give the necessary efficiency without undue complication or expense. The steam-gas turbine in which steam is used in the state of a gas at a high temperature throughout the process of conversion into work, gives theoretically a high efficiency at workable temperatures, and I believe will, in course of time, supply the necessary means of conversion for effectively turning our coal into electricity. I have therefore considered the case on these lines.

In order to produce the supply of 131,400 million Board of Trade units at a 60 per cent. load factor, machinery of the normal capacity of 25 million kilowatts would have to be installed.

For the purpose of estimation it may be considered that this capacity would be divided up into 100 stations of the capacity of a quarter of a million kilowatts. Each of these stations would contain

10 generators of 25,000-k.w. capacity. These stations would be spread about the country to supply the demand in each part roughly proportional to the coal now consumed.

The positions of the actual generating stations would be largely controlled by the facilities for obtaining coal and water for condensing. In many cases they would be close to the colliery districts, and the current would be transmitted to the points of demand.

In other cases, where a considerable demand was concentrated at a distance from the sources of coal supply, and where the coal could be cheaply carried—especially by water—stations would be installed and would supply electricity to meet the surrounding demand. In all cases, however, whether far from, or near to the coal production, the coal would be delivered in very large quantities to only a few points of consumption, and would thus reduce the labour and cost of transmission and handling to the lowest figure.

Many works taking a large quantity of electricity for metallurgical and chemical purposes at a very low price would be built adjoining the generating stations, and other existing works would be at such short distances that the capital costs for distribution of the electricity which they used would be very small.

Estimating on the basis of the typical generating station considered and multiplying by the number of stations, I have put down the capital cost of generating works at £7 per kilowatt, which, for the total kilowatts required, gives an expenditure of 175 millions sterling. The cost involved in the distribution system on such a scale is difficult to estimate. The conditions of demand in relation to the position of the supply stations would, however, be favourable, as a great deal of the energy required would be transmitted only short distances, and units of demand would be large. Under the circumstances, I believe that £13 per kilowatt would be amply sufficient, and a sum of 325 millions sterling would thus cover the cost of the distribution system.

The total cost of the scheme, including all expenses up to the point of delivering the electric supply to the consumer, would thus be 500 millions sterling. This, of course, is a very large figure, but, considered in relation to other industries and the results to be accomplished, cannot be considered excessive.

It has been estimated that the capital now invested in this country in electrical undertakings amounts to some 400 millions sterling. Last year the Electric Supply Business had invested in it some 58 millions sterling. The proposed scheme would therefore absorb from eight to nine times the amount of capitital now invested in the portion of electric supply undertakings for which figures are available. The units generated upon the all-electric method of working would, however, be some 150 times as great as those generated by the above undertakings, and the cost of production and sale price of current would, of course, be very much lower than at present.

The cost of producing the electricity required under the scheme may now be considered. Capital costs taken at 8½ per cent. upon the money

invested, form by far the most serious item, and amount to 0·0776d. per unit, or a total of £42,500,000 per annum. The works costs would, I believe, not exceed 0·036d., bringing up the total costs, including interest and all other charges, to 0·1145d. per unit, or 62 millions sterling per annum.

In arriving at the above figures for the costs of generation 60 million tons has been taken as the annual coal consumption, and this has been charged at an average price of 10s. per ton, thus amounting to 30 millions sterling. On the other hand, it has been assumed that with improved processes of conversion, 1 ton of coal will yield fixed nitrogen equivalent to 1 cwt. of sulphate of ammonia. The present price of this commodity is well over £12 a ton, but considering the large scale of production and the necessity of supplying it at a low price to make its use general for agricultural purposes, I have reckoned the fixed nitrogen as of a value of only £8 per ton of sulphate of ammonia or, on the 3 million tons to be produced, of 24 million pounds sterling. This reduces the cost of the coal to 6 millions sterling, which largely accounts for the low works costs.

The cost of chemicals required to make the fixed nitrogen available together with the necessary labour involved in the process, would be met by the sale of the other coal by-products—principally consisting of tar and oils.

It is, of course, well known that firing by means of gas compares unfavourably with using the coal direct. It is also generally found that a good return of fixed nitrogen in the form of ammonia is only obtained from the coal at a sacrifice of thermal efficiency, and also involves a much smaller yield of the other by-products which can be extracted from the coal, but now that the importance of these matters is realised a great deal of work is being done to improve the processes, and eventually it will undoubtedly be possible to obtain the high return that I have spoken of without sacrifice in other directions.

Following upon the costs of electric generation already discussed, I have assumed, for the purpose of comparison, that the average price at which current would be supplied throughout the country would be ⅛d. per Board of Trade unit. The charges would not be uniform, but would be graded according to the position and nature of the load supplied.

It is interesting for a moment to consider the effect of such a supply of electricity upon its present and future uses.

Taking lighting to begin with, which was the first application for which a supply of electricity was generally given, it will be clear, considering the strong position which electric lighting now holds even with current at an average price of 2d. per Board of Trade unit, that when it is obtained from current at the much lower prices that would rule under the all-electric scheme no other form of light would have a chance in competing with it.

Notwithstanding present high prices, a good deal of electric cooking and heating is already being done, and although it would appear

to be too expensive for general application, still the very good results obtained and the large amount of labour saved is already sufficient to justify its use to-day.

When electric heating and cooking are carried on with current at the very low figures at which it would be possible to sell for these purposes, it would only be a matter of time for all heating and cooking to be done by means of electricity.

Regarding the supply of power, electricity is now admittedly the most convenient form of power for all purposes, and this, again, notwithstanding the costs involved on the comparatively small scale on which we now produce. The overwhelming advantages of electric power at a price at which it would be supplied on the all-electric scheme would clearly ensure its use for all power purposes.

The case with regard to electric tramways and light railways is well known, and any reduction in the costs of running due to cheaper current would, of course, act greatly in favour of these undertakings, and would help to extend their usefulness. Light railways, which, for various causes, have made such poor progress, if sensibly dealt with, would greatly benefit by finding a cheap supply of energy available in all parts of the country.

The electrification of main-line railways has not yet progressed very far, as it is hard to make out a sufficiently strong case to warrant the large expenditure necessary for electrification; but there is little doubt that growing traffic, which necessitates additional works, will be best met by electrification, which will enable a greater return to be obtained from existing lines and works. The electrification of our railways would be greatly assisted and made a more profitable investment if a supply of current at such a figure as we are now considering were available for their working.

The manufacture of pig iron is, no doubt, quite the most economical use of coal that we now have, but recent work with electric smelting furnaces has shown that it is only necessary to have electric current at a low enough price and for sufficient experience to be obtained to make it more economical to smelt iron electrically than by present methods, and using only sufficient coke to provide the carbon for the purpose of reduction.

It may be taken, from the experiments already made, that when worked on a sufficient scale a quarter of a ton of coke would be required per ton of iron produced, and that 4 tons of iron would be obtained per kilowatt-year. This would mean that about 0·42 ton of coal would have to be converted into coke and used per ton of iron, together with about 2,200 Board of Trade units, which, at $\frac{1}{12}$d., would come to 15s. 3d. per ton of iron. As the electric furnaces would no doubt closely adjoin the generating station the price named for current would be a very good one. We should thus have a cost for coke and electricity of about 19s. 6d. per ton of iron produced.

According to the recent Report of the Royal Commission on Coal, pig iron, on the average, now requires about 2 tons of coal per ton of

iron produced, and taking this at the same price as coal has been taken for the purpose of electric generation, viz., 10s., this would give 20s. as the cost of fuel per ton of iron produced. It is, however, probable that the production of pig iron electrically with current supplied to the works would involve less plant and a less upkeep of plant than at present: also a good deal less labour would be required. Improvements in the process brought about as the result of experience would, no doubt, further reduce the costs, and would result, in all probability, in a better article at a lower price.

We at present produce about 10 million tons of pig iron. This would therefore require 2½ million kilowatts of plant run continuously and producing 22,000 million Board of Trade units annually. In order to get current for this purpose at the lowest price, it would in all probability be found desirable to insulate the furnaces to avoid heat loss, and for the same reason to have individual furnaces of a very large capacity. It would then be possible to work intermittently and yet with economy, and so use the current taken by the furnaces to fill up the load curve, thus adding to the economy of conversion and reducing the capital expenditure involved in electric plant.

Steel-making electrically is already in extensive use, and even with present facilities for generating the current which the process requires is beginning to make considerable headway. All steel would, of course, be produced electrically as soon as sufficient experience had been gained regarding details and a supply of very cheap current was available.

Foundry work in both iron and steel would be most conveniently carried out by means of electric melting. It is already known that the electric furnace gives the best results obtainable for steel castings.

The heating of steel for rolling, forging, and annealing will be most efficiently carried out electrically as soon as the cheap supply warrants experimenting in this direction. In fact, all furnace work for which coal or gas are now used could, I am convinced, be more satisfactorily done electrically when an abundant and cheap supply is available.

We now use aluminium for a number of purposes, notwithstanding our want of knowledge as to the best ways of working it. When our experience with aluminium in any way approaches what we now know about the working of steel, it is certain that vast quantities of this material will be used throughout the world. The manufacture of aluminium is another of the processes which will be greatly facilitated by a cheap supply of electricity. In fact, it may be said that aluminium can only be produced economically at present in water-power countries, but as an intermittent supply of electricity could be given under the proposed scheme at a lower price than it is being obtained from water powers, we should be in a better position than the water-power countries to manufacture this metal.

With cheap electricity available, electro-chemical processes must grow and multiply to an enormous extent, and not only should we produce for ourselves all the chemicals which are now produced elec-

trically abroad, but everything that can be produced electro-chemically would then be made in this country.

There is a further application of the electric current which, so soon as the price was low enough, would, no doubt, largely come into use. This is the intensive growing of fruit and vegetables under glass. It is known that considerably more forcing in the way of heat can be advantageously applied where light is also furnished artificially, and it is therefore probable that, with electricity everywhere available at a low price, an immense amount of intensive cultivation under glass with the heat supplied by means of the electric arc would be undertaken, as in supplying heat by this means light would also be supplied, which would have the effect of enabling the growth to benefit fully by the artificial heat.

Summarising the whole position, it may safely be said that, wherever coal, gas, or power are now used, everything for which they are used will be better done when electricity is the medium of application.

Hardly less in importance in the all-electric scheme is the question of the by-products which become available by the proper use of our coal. These consist principally of fixed nitrogen, together with tar and oils.

Fixed nitrogen in the forms of sulphate of ammonia, nitrate of soda, and nitrate of lime are most valuable fertilisers, and enable land continually to produce the same crops with a greatly increased yield per acre. Much has been done in finding out how best to utilise these artificial fertilisers, but no doubt a great deal more will be done in this direction, and fertilisers will be prepared, with fixed nitrogen as their principal constituent, which best suit the particular soils and crops that it is desired to deal with.

According to last year's Board of Trade returns we now grow about 23 per cent. of the total wheat that we use and import 77 per cent. Of the barley used we grow 59 per cent. and import 41 per cent., and of the oats used 78 per cent. is home grown and 22 per cent. imported. Last year we devoted 7¾ million acres to the cultivation of these crops.

Much is being done to improve the yield of corn crops, and it is probable that with scientific treatment in the production of the seed, in the sterilisation of the ground, and in the application of fertiliser, we may look at no distant date to an increased yield of 50 per cent. in these crops upon what is now being produced per acre. The most vital feature, however, in bringing this about, once we have acquired sufficient knowledge, is an ample supply of fixed nitrogen to use as fertiliser, and it is when considered from this point of view that a scheme which supplies this from our coal as the result of saving present waste is most important.

With the increased yields which we have mentioned we could produce corn crops sufficient to supply the whole of our requirements upon 11 million acres. This would represent 23½ per cent. of our present cultivated area, and would only be an addition of 3¼ million

acres to the land now used for the purpose of growing these same crops. The value of these additional crops would be about 58 millions sterling, based upon the prices which we paid last year, and to this would have to be added the value of the straw and the other wheat by-products, which would go a long way towards providing the food for growing the additional meat which we require to supply our demand at home.

In order to fertilise the land, we should have available, under the all-electric scheme, 3 million tons, or its nitrogen equivalent, of sulphate of ammonia. This, if used over the whole of the 46¾ million acres now under cultivation, would give 143 lbs. per acre, but, of course, the fertiliser would be distributed according to the nature of the land and the crops being grown. It is probable that under these circumstances the increased yield of the land now cultivated would not only give us all the grain that we should require for food, but also all the foodstuffs, partly as by-product from the grain and partly grown, that would be required for raising the cattle, sheep, and other animals necessary to supply the whole of our wants.

It is now beginning to be understood that intensive farming of the land also involves intensive cattle raising, and that it is very advantageous greatly to reduce the amount of grass land and instead to grow crops intensively cultivated, as in this way a given amount of land can be made to produce a much larger yield.

Sulphate of ammonia is a particularly good fertiliser for the purpose of growing sugar beet, and here again it is probable that the availability of large quantities of this fertiliser at a very much lower price than at present prevails would enable us to produce the whole of our sugar at home, especially as the by-product obtained in the form of crushings from the beet is a very valuable food for cattle raising, and also as the crop is a very suitable one for growing alternately with wheat.

If it was found that a larger amount of fertiliser than the 3 million tons of sulphate of ammonia, which would be the principal by-product from the 60 million tons of coal turned into electricity, could be advantageously used, this would be very economically produced from the electrical station by the oxidation of atmospheric nitrogen, giving a valuable fertiliser in the form of nitrate of lime. This could be made intermittently by means of current filling up the load curve and would not necessitate the expenditure of any more money on plant for generation or transmission of the current. It would, however, require the burning of additional coal, and this in itself would add to the sulphate of ammonia available.

The output of the 25 million killowatts of plant installed has been reckoned upon a 60 per cent. load factor, but it is quite possible that the load curve could be still further filled up by an additional 20 per cent. for any purposes such as those just stated. In this way it would be possible to burn an additional 20 million tons of coal annually, producing a million tons of sulphate of ammonia and other by-products,

and 43,800 million additional units, which could be sold at a considerable profit at $\frac{1}{10}$d. per unit, as the cost would not exceed $\frac{1}{50}$d. per unit.

A certain proportion of this extra supply of current could be used to fix nitrogen in addition to that obtained direct from the coal, should this latter supply be insufficient for the country's wants, and the balance of the current used for electro-chemical or other requirements which could take power intermittently.

In this connection it must be remembered that an intermittent or controlled make-up load may be intermittent to the extent of 80 or 90 per cent. of the load, a certain amount of current being always kept on to make up for heat losses in furnaces or to prevent reversal in electro-chemical work.

If the whole of the additional output could be taken up the effect of the increase of revenue, together with the difference on the original figures of selling the first 60 per cent. at an average of $\frac{3}{8}$d. instead of at the lower figure of 0·1145 of a penny already mentioned, would enable 10$\frac{3}{4}$ per cent. to be allowed on the capital instead of 8$\frac{1}{4}$ per cent. already provided for.

It is assumed by many people that the climate of this country is largely unsuitable for the purpose of growing food, and for this reason it is thought that we can never grow the food which we require. This is largely a misconception, as crops both large in quantity and of good quality can be produced in this country. Nevertheless, it would be a desirable thing if, instead of the dark weather that we now often experience owing to cloud obstruction, we could have continuous sunshine at certain times of the year. The amount of sunshine would, no doubt, be largely increased by the abolition of all smoke in the air, as not only does the smoke itself obscure the sun but also it seems to have the effect of assisting the formation of cloud, which greatly diminishes the light and heat which we receive.

At present it is considered quite right and reasonable to canalise rivers and make great works for adding to the fertility of countries by means of irrigation, but I believe that in the future the time will come when it will be thought no more wonderful largely to control our weather than it is now thought wonderful to control the water after it has fallen on the land. I think that it will be possible to acquire knowledge which will enable us largely to control by electrical means the sunshine which reaches us, and, in a climate which usually has ample moisture in the atmosphere, to produce rainfall when and where we require it.

It seems to me that it may be possible, when we know a great deal more about electricity than we do to-day, to set up an electrical defence along our coasts by which we could cause the moisture in the clouds to fall in the form of rain, and so prevent these clouds drifting over the country between ourselves and the sun which they now blot out. It also seems to me that it will be possible, when more water on the country is required, to cause the falling of rain from the clouds passing

over the highest part of the country and so produce an abundance of water which, properly used, would greatly add to the fertility of the country.

Of course, it may seem that these are only mad visions of the future, but I think we can hardly consider these results more improbable than any one would have considered wireless telegraphy or flight in heavier than air machines fifty years ago. My excuse for mentioning these matters here is that they might constitute another great use of electricity, and their useful consummation would certainly be facilitated by an abundant supply of electrical energy.

There would be further by-products from the coal in the form of tar and light oils. The effect of their abundant production and sale at a low price would be most important to the country, as the large quantity of tar produced would enable us to make good roads, which we much need, and which would have the lowest cost of upkeep, and the light oils would, when carburettors have been further developed, go a long way towards supplying the fuel for our motor-cars and other motor vehicles which we now have to import from abroad.

As there must be an enormous development in the way of motor traction these two by-products become most important. The necessity for labour-saving appliances used in agriculture must greatly add to the number of motors which cannot, according to present knowledge, be replaced by electricity, and these, no doubt, would be made to burn the heavier oils which would be produced as part of the coal by-products.

Considering the general effect of the all-electric scheme, in which, with but small exception, the whole of the coal used is turned into electricity, the first important effect would be the saving of some 80 to 90 million tons of coal a year. As we should produce the whole of our food requirements, we should not have to export our capital in the form of coal to help pay our food bill. In this way, by making these two savings, we could prolong the useful life of our coal measures two and a half times, and still have 20 million tons of coal a year available for the use of our steamships over and above the coal required in the country.

The saving of labour now employed in raising the vast amount of coal which we now waste or send abroad, and also the labour employed in transporting this coal and using it for all the various purposes for which it is now required, together with the labour employed in cleaning up and getting rid of the effects of burning coal according to our present methods, would all be available for additional manufacturing of the articles now imported and for use on the land.

The saving of so much wasted labour and material would greatly add to the prosperity of the country and so enable us to support a larger population living under more healthy and comfortable conditions than at present.

Cheap electricity would greatly stimulate all manufacturing opera-

tions, which would, in turn, enable labour to be much better remunerated than at present, and to enjoy a much higher standard of comfort. The higher value of labour would in its turn stimulate inventiveness and the production of all sorts of labour-saving appliances which, with cheap electricity, would enable us to produce in the future under suitable market conditions at cheaper rates than are now possible, notwithstanding the better return that labour would obtain.

Great hardships are always produced where any great industrial change is made, but the more efficiently we can carry on the work of the country the more margin must there be for the great majority of the people: so that any change which decreases the amount of labour required must eventually give the people greater comfort and less arduous work. It is hardly necessary to point out how much better the position of the country would be if we were producing the whole, or nearly the whole, of our requirements, as in this case we should be far less liable to be adversely affected by any external causes or by the occurrence of any great war.

At present, although the using of our coal may mean commercial activity it certainly means the desolation of the country in parts where it is largely used. Instead of this harm being done to the country by our coal, we should fertilise the lands by its means and might even, as I have indicated, use it in the future to increase our sunshine.

Of course there are many things which at present stand in the way of realising such a scheme as I have outlined. There are many technical details which nothing but an immense amount of work can solve satisfactorily. There are also political and legislative difficulties standing in the way, but these, when the time arrived, would have to be got rid of rather than allow them to handicap the advance of the country. The more, however, that I have considered these ideas in detail, the more certain am I of the fundamental soundness underlying them and that it is only a matter of time before such a scheme is carried out in its entirety.

What interests us most, perhaps, is the question of how long it is likely to be before the all-electric idea becomes possible. At present there is so much required to be done to make it workable in all its details that it seems as though its realisation would be long deferred. It must, however, be remembered that knowledge is continually being acquired which brings us nearer to its realisation, and that things engineering, and especially in electrical engineering, now move very rapidly. It may therefore come to pass that the all-electric idea, with its far-reaching changes and great benefits, will become an accomplished fact in the near future.

Mr. R. K. GRAY: Ladies and Gentlemen,—It is my pleasure to lay before you the following resolution: "That the best thanks of the Institution be accorded to Mr. S. Z. de Ferranti for his interesting and instructive Presidential Address, and that, with his permission, the Address be printed in the *Journal of the Proceedings* of the Institution." Mr. Gray.

Mr. Gray. I am sure we have all listened to our President's Address with a great deal of interest. The occupancy of the chair on such an occasion as the present, carries with it a great advantage in that one can speak quite freely and without fear of contradiction, and this freedom enables the speaker to irritate the minds of his hearers in such a way that some real progress is likely to result. Our President has taken full advantage of this immunity, and has given us all a great deal to think about. I am sure I am expressing the feeling of the meeting in thanking Mr. Ferranti for the pains he must have taken in the preparation of his valuable address, and for the food for reflection he has laid before us. We all sincerely hope that he may live long enough to see realised some of the advantages that may come from our action provoked by the address we have just heard.

When I have been abroad I have met people who have asked me, "Is Mr. Ferranti still alive." In spite of our President's actual years and his appearance we cannot wonder at people asking this question as so many years have elapsed since his name came first into public view.

Should any doubters exist their doubts will be dispelled when our President's Address reaches them, as it distinctly shows that Mr. Ferranti is very much alive.

Dr. Glazebrook. Dr. R. T. GLAZEBROOK : Ladies and Gentlemen,—I rise with great pleasure to second the motion that Mr. Gray has put before you. Before we heard the President's Address we were all ready to give him a warm welcome. We were ready to welcome him as a pioneer whose work has done so much for electrical engineering through those many years in which he has been actively engaged in it. We knew that from him we should have a brilliant and original address, and we have learnt to-night, I think, something of the value of the imagination in science. It is good to give rein from time to time to the imagination even in our daily prosaic work. Mr. Ferranti has been a prophet in years before, a prophet speaking sometimes, it may be, to deaf ears. It is a pleasure and a privilege to the Institution to honour their prophet in their country. All of us cannot hope to live to those happy days when electricity will be sold at the rate of $\frac{1}{8}$d. per unit, but those of us who do, and those among our children who are alive when those days come, will look back to this evening as an historic occasion ; and those of us who are still alive will be glad that we have taken, at any rate, some part in it by listening to the address.

I have now great pleasure in putting to you the resolution moved by Mr. Gray : "That the best thanks of the Institution be accorded to Mr. S. Z. de Ferranti for his interesting and instructive Presidential Address, and that, with his permission, the Address be printed in the *Journal of the Proceedings* of the Institution."

The resolution was then put and carried by acclamation.

The President. The PRESIDENT : Mr. Gray, Dr. Glazebrook, Ladies and Gentlemen, —I am most deeply grateful for the very kind way in which you have proposed this vote of thanks, and for what I feel are the very happy

The President.

remarks that you have made. Mr. Gray has said that I may so have irritated the minds of the listeners that good would come out of what has been said. I hope indeed that I have very much irritated everybody in this way. I knew that I was taking a most contentious subject; I wished to irritate; I wished to stir up; I wished to electrify the industry, and the country too if I could, to do better things than at present, and to push forward on a policy of development which would lead to great benefits in the future. Especially I wished that our Institution of Electrical Engineers might help to lead the way in progress and advancement, so that we might be worthy successors of the very great men in electricity who have gone before us.

I have to thank you most heartily for having elected me as your President for this year, and I can only assure you that it will be nothing but the greatest pleasure to do what I can for the Institution.

The meeting adjourned at 9.30 p.m.

Proceedings of the Five Hundred and Eleventh Ordinary General Meeting of the Institution of Electrical Engineers, held on Thursday, November 24, 1910—Mr. S. Z. DE FERRANTI, President, in the chair.

The minutes of the Ordinary General Meeting, held on November 10, 1910, were taken as read, and confirmed.

Messrs. C.W. Smith and J. O. Girdlestone were appointed scrutineers of the ballot for the election of new members, and, at the end of the meeting, the following were declared to have been duly elected :—

ELECTIONS.

As Members.

William Beverley Boyd.
Donald Murray.
Robert Patrick Sloan.

As Associate Members.

Charles William Appleby.
Gilbert Archer.
Arthur Thomas Arnall.
Harold Eustace Blake.
William Henry Bradbury.
John Brownell.
Percy Harold Buzza.
William Alexander Christianson.
Charles Henry Farley Fox.
George Pollard Dennis.
Leonard Charles Desbruslais.
Norman Donkersley.
Richard Netterville Eaton.
Thomas Ellis.
Arthur Leonard Johnson.
Douglas Kerridge.
Alan Kirk.
Herbert Ross McClymont.
Walter Edward A. Morby.
William Napier.
George Paton.
Thomas Edward Robertson.
Mostyn Rosenbaum.
James H. Ryder.
James Vincent Stanton.
William Joseph Wayte.

As Students.

Horace Algar.
Arthur Arnold.
Henry Arthur Browett.
Brian Andrew G. Churcher.
Banarsi Das Jain.
Donald Nisbet Jenkins.
Edward Alfred Martin.
Harold Neville Munro.
John Stagno Navarra.
Hapet Papazian.
William Parry.
Lyndall Crossthwaite Pocock.
José Tyuca Radcliffe.
James Francis Riley.
Bernard Augustus Robinson.
John Periam Rowell.
Henry Edward Sanders.
Brijo Krishna Sibou.
Haworth Walter Trefusis.
Dhanjishaw Hormusji Umrigar
Harold Kenneth Whitehorn.
William Edward Woodward.
Esdaile Wyatt.

The following paper was read and discussed : "Street Lighting by Modern Electric Lamps," by Haydn T. Harrison, Member (see page 24).

The meeting adjourned at 9.50 p.m.

STREET LIGHTING BY MODERN ELECTRIC LAMPS.

By HAYDN T. HARRISON, Member.

(*Paper first received January* 25, 1910, *and received in final form November* 1, 1910. *Read before the Institution November* 24, 1910; *before the* MANCHESTER LOCAL SECTION *November* 22, 1910; *and before the* BIRMINGHAM LOCAL SECTION *December* 14, 1910.)

In the very early days of electric lighting the streets which, owing to their importance, required increased illumination, were changed from gas to high candle-power lamps, such as arc lamps; but, unfortunately for electrical engineers, these streets were few in number compared to the thousands of miles of less important streets and roads which were and are lighted by incandescent gas lamps. Moreover, the high candle-power arc lamps which electrical engineers had at their disposal for competitive purposes gave their maximum candle-power at an angle requiring that they should be placed at a considerable height, and at a short distance apart when required to obtain an even illumination, which resulted in a high cost per mile of lighting. The improvements connected with electric lamps which have taken place within the last two years have placed electrical engineers in a very different position, not only as regards large units of light, arc lamps being now available which give their maximum candle-power in the direction most suitable for street lighting, but also with small units of lights, incandescent lamps, such as tungsten lamps, being available, which give four times the candle-power of the carbon lamps for the same consumption of energy. It was the advent of these efficient small units of light that gave electrical engineers an opportunity of competing favourably with gas for side street lighting, as they can be installed without a heavy outlay in capital. And as most of the streets are sufficiently well illuminated by small light units a very large and valuable load results.

At the commencement of this paper I wish to refer to a statement made by Dr. Louis Bell before the Illuminating Engineering Society of America, namely: "Street lighting has been a growth and an evolution, but like all growths it has proceeded to a certain extent along the lines of least resistance; lamps were put, not in the best places for them, but where they could be put in with the least disturbance to individuals." This I have found to be a correct statement of fact, and therefore the engineer of to-day who takes up the question of street lighting will often find that he is required to improve the illumination

of the streets, not by rooting up the existing standards and placing whatever sources of light he may have at his disposal in the position suitable for such sources, but by increasing or adjusting the candle-power at the existing points so as to give the best illuminating results at a cost not exceeding and more often less than the existing rate.

In nearly every town and city of this country, gas, being the illuminant available at the time when the streets were built, was naturally chosen for the purpose, and electrical engineers have found that in order to displace it they must be in a position to supply lamps of about the same candle-power either at an equal or a lower cost, as it is often not considered advisable to go to the expense of scrapping existing posts and lanterns. I propose, therefore, to lay before you the figures relating to the borough of St. Marylebone, where the incandescent gas lamps have lately been replaced by electric (tungsten) lamps. In this case the procedure was as follows: The Electricity Supply Department to the Council was advised by their consulting engineer to ascertain exactly the illumination given by the existing gas lamps, and an outside testing authority intimately connected with the gas industry was instructed to test at random 100 street gas lamps in the district. The results showed an average for the single 4½ cub. ft. gas mantles of 50 c.p. and 76·6 for the double mantles. Mr. Arthur Wright having discussed the matter with me, I tested for my own satisfaction and found that with the single mantles I obtained an average of 45 c.p. and with the double 76 c.p. It was decided that the single lamps should be replaced by two 115-volt 35-watt Osram lamps in series, and the double lamps by two 55-watt lamps. It was then necessary to decide upon the best type of fittings to use, the consideration of which was governed by two important factors—namely, capital cost and effective appearance.

The existing gas lamp-posts and lanterns being the property of the Council, and having been maintained in good condition, it was decided to retain them. The light from tungsten lamps having a profile curve favourable to street lighting it was only necessary to accentuate this by means of reflectors; on the other hand, the use of something which would counteract the effect of high intrinsic brilliancy of the light source on the iris of the eyes had proved in my experience a very important point; therefore I submitted a reflector for this purpose which, after slight modification to suit local conditions, was duly approved. This reflector, which is in shape similar to an inverted wedge with suitably curved sides, attained both of the above objects, increasing the candle-power of the rays near the horizontal to nearly double that of the lamps only and to six times the vertical rays. It is unnecessary to describe the apparatus used as it must be well known to most of you who at some time or other have passed through the streets of Marylebone. I will therefore only enumerate the chief features, namely, a large surface of white reflector above the lamp filaments with no intervening lamp caps or holders thus attaining the objects mentioned above; anti-vibration holders to protect the lamps from harm due to street vibration, or jars when switching on or off; suitable

watertight D.P. switches and fuses and sealing chambers of sufficiently small dimensions to go between the bottom of the lantern and the top of the post; all of which were designed in such a way that they could be erected at slight cost. It was estimated that the capital cost of converting 1,964 lanterns and connecting them to existing distributors would be £8,000, but owing to excellent systems adopted by the mains engineer of the Council and his assistants the work has actually been done for £5,788, or an average of less than £3 per post, and when it is borne in mind that this work was carried through in three months at an average of nearly 200 posts a week without in any way interfering with the continuity of supply to a single customer, great credit is due to the organisation of that department.

The excellent results obtained have led to the Council deciding to convert the remaining 1,385 lanterns in this district, but owing to these not being adjacent to existing distributors, new ducts and mains were necessary. As these would, of course, eventually have to be laid for private lighting and power supply it is difficult to allot the right amount of capital charges to the public lighting, but even if the whole of this were allotted to public lighting based on a 25-year loan, and the cost of the electric fittings be repaid in 3 years, £1,640 would still be available for electric supply if the existing gas rate were still charged for lighting. This is equivalent to 0·9d. per unit for the first 3 years and 1·17d. per unit thereafter. The 1,964 lamps when lighted by gas cost the Council for gas, lighting, extinguishing, cleaning, and maintenance, £8,818 per annum. The gas contractors when asked for a revised tender reduced their price considerably, but were unable to compete with the tenders of the electricity department, which amounted to £7,350 per annum made up approximately as follows:—

		Per Post.		
	£	£	s.	d.
A. Electrical energy at 1·42d. per unit ...	3,950	2	0	0
B. Lighting, extinguishing, cleaning, painting, etc.	1,570	0	16	0
C. Lamp renewals	1,230	0	12	6
D. Repayment of cost of electric fittings in three years	600	0	6	6
Total	7,350	3	15	0

It must be remembered that 1,964 street lanterns included in this charge contain lamps of various candle-power; the number are approximately as follows:—

	Measured Candle-power. At 20°.	At 10°.
335 two 80-watt lamps	135	220
491 two 55- „	75	130
1,138 two 35- „	55	100

In dividing them the proportionate cost of each would be approximately as follows when taking energy at 1·42d. per unit :—

	70 watt.		110 watt.		160 watt.	
	s.	d.	s.	d.	s.	d.
A	28	6	45	0	64	0
B	16	0	16	0	16	0
C	12	0	12	0	15	0
D	6	6	6	6	6	6
Total ...	63	0	79	6	101	6

(Each per annum.)

In the above figures the price charged per unit is 1·42d. This figure was not arrived at with any idea of the cost to the electricity department, but in order to repay the cost of the services at an early date. It will be noted that if the charge per unit had been 1d., which is more consistent with the costs of generating, the sum of £3,950 per annum would be reduced to £2,780, which allows £1,170 per annum for repayment of cost of services, etc., the cost of the repayment of the electric fittings being already allowed for ; this will easily wipe off the cost of the services in five years ; therefore, if a 10- or 15-year loan had been arranged the price per unit could have been reduced to 1d. per unit, which would work out as follows :—

	70 watt.		110 watt.		170 watt.	
	s.	d.	s.	d.	s.	d.
A. Electrical energy at 1d. per unit ...	24	0	38	0	56	6
B, C, and D. As before	34	6	34	0	37	6
Total	58	6	72	0	94	0

NOTE.—Charges B and C have since been reduced, thus an actual higher rate is being obtained for current.

This brings up the important question of allotment of capital charges. It seems incomprehensible to me that capital charges connected with the services to street lamps should be dealt with differently to those

necessitated by an ordinary consumer, and that the loan for them should ever be refused. As a consumer, a street lamp is very attractive, the load factor is good, no expensive meters or other apparatus are necessary, and it is not likely to have to be cut off owing to termination of tenancy or vagaries of that description. The street lamp acts as an advertisement to the electricity undertaking, and the local authority controls its own public lighting instead of being in the hands of its bitterest opponent. In the case of Marylebone, not only were all these advantages gained, but a large saving—namely, £1,500 a year—was made

Original.	Candle-power.	Replaced by.	Candle-power at 20°.	Candle-power at 10°.
Single gas mantle	45	2·35 watt Osram lamp	55	100
Double gas mantle	76	2·55 watt Osram lamp	78	130
Double gas mantle	76	2·80 watt Osram lamp	135	220

(These tests were carried out by the author under identically similar conditions.)

in the lighting rate, the electricity undertaking benefited, and the illumination of the streets was improved. In the face of all this it would be interesting to know on what grounds the authorities who control the obtaining of loans by municipal undertakings base their antipathy to granting loans for street-lighting purposes. As mentioned above, the illumination of the streets of Marylebone has been improved by the conversion. The tests on the gas lamps mentioned previously are compared with tests on the electric lamps as shown above.

In total candle-power, these figures are very striking, the—

1,964 gas lamps gave a total of 109,000 c.p.
1,964 electric lamps give a total of 146,000 c.p. at 20°, 193,883 at 10°.

As regards the illumination, this was, of course, increased directly in proportion to the increase of candle-power as the position, height, etc., of the lamps remained the same.

The number of posts to the mile varies with the importance of the thoroughfare or street, and also the width of the roadway. The above results take these two factors into consideration, and are calculated from actual candle-power measurements in the street.

It is interesting to note from a previous paper by the author * that the figures given as an average minimum *direct* illumination taken from a large number of important towns came out as follows :—

* *Journal of the Institution of Electrical Engineers*, vol. 36, p. 188, 1905–6.

	Average in 1905.	Marylebone, 1909.
Main thoroughfares ...	0·050 c. ft.	0·15
Side streets...	0·025 "	0·048 to 0·07
Suburban streets	0·005 "	—

In the important thoroughfares there are an average of 76 posts to the mile, and in the less important streets 65 posts to the mile, so from the above it will be seen that at 1·42d. per unit the cost per annum works out at :—

	£
Main thoroughfares	384 per mile.
Side streets	204 "

Or if electrical energy be taken at 1d. per unit, the cost would be :—

	£
Main thoroughfares	356 per mile.
Side streets	190 "

Before leaving the subject of the Marylebone lighting, it is necessary to consider a third type of thoroughfare, namely, Oxford Street. With the exception of London and some of the more important towns, there are few places where it is necessary, or where the authorities could afford to illuminate any streets up to the degree attained in Oxford Street; nevertheless, it is interesting to ascertain the cost of illumination up to this standard where necessary, and also to what extent the present cost could be reduced by modern appliances. At the time Oxford Street was changed from gas to electric lamps the most efficient lamps available for the purpose was the converging carbon flame arc lamp. This lamp was therefore used, the globes being of the opalescent type recommended by the makers at that time. Two such lamps were erected on centre poles where favourable, which were at distances of nearly 200 ft., this resulted in a minimum horizontal illumination of 0·11 c. ft.; thus it will be seen that the cost of this type of lamp works out at nearly £20 per annum. The results are roughly as follows :—

Oxford Street.

Minimum Horizontal Illumination.		Cost per Annum per Mile.
0·11	... ...	£800

Since that time the arc lamp makers have turned their attention to altering the distribution of light from flame lamps in order to make them more suitable for street lighting.

For instance, in the case of arc lighting it is difficult to arrange for the arc when erected on posts to be higher than 25 ft. from the ground, and the distance between them is rarely less than 150 ft., and is sometimes as much as 300 ft., therefore the light rays which reach the point of minimum illumination are those which emanate at 10° to 17° from the horizontal. Some tests which I have lately conducted in Oxford Street, Oxford Circus, and Regent Street proved these rays to be of the following candle-power (see Curve II.) :—

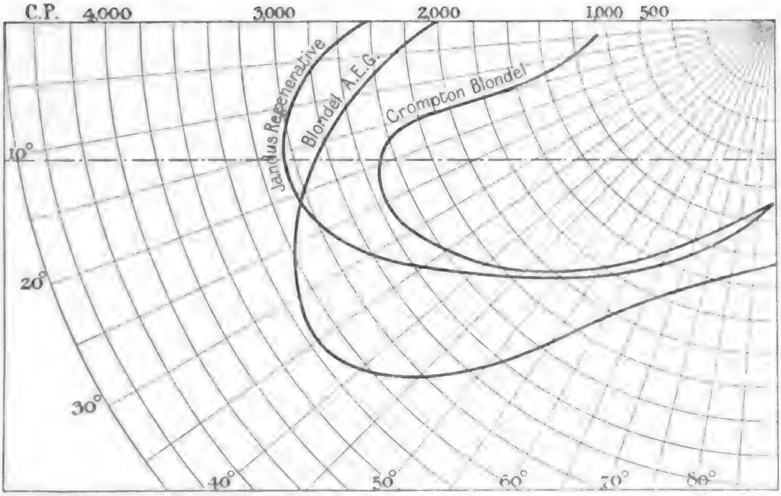
10-ampere Union flame arc lamp, opalescent globe, 10° to 15°	1,100–1,200 c.p.
10-ampere Union flame arc lamp, dioptric and opalescent globe, 10° to 15°... ...	1,750–1,800 „
12-ampere Union flame arc lamp, dioptric and clear globe, 10° to 15°	3,700–4,400 „

This already indicates the advance one firm—namely, Koerting and Matheson—have made in the right direction by the introduction of the dioptric globe; for example, if these dioptric globes are used the increased illumination is 60 per cent., without appreciably increasing the cost of maintenance. If a clear outer globe is used the illumination is more than doubled. But Koerting and Matheson are not the only arc lamp makers who have appreciated the importance of light distribution. Messrs. Crompton, with the Crompton-Blondel lamp, and the Jandus Arc Lamp Company, with their regenerative flame lamp, have both made a great advance in this direction, as has been already demonstrated from the valuable tests carried out by Mr. J. T. Morris * at the East London College. Table I. (page 32) is compiled from Mr. Morris's figures and further tests taken by myself.

The above figures refer to tests made on the lamps when using the carbons recommended by the makers, which in every case are high-grade carbons with the exception of the magazine lamp, which is a low-grade carbon lamp. These figures can only be taken as a rough guide on account of the question of globes, and also the current at which the lamps are run, which makes far from proportionate difference, low-current arc lamps being always much lower in candle-power output per watt than those taking more current, and this particularly applies to flame lamps. The vertical carbon lamps, though of much higher efficiency, are not so steady burning as the inclined carbon lamps on account of the movement of the arc. I have found in the street when photometering that this variation is sometimes 50 per cent. As regards globes, the absorption of these differs enormously, and the greatest care should be taken in their selection, the only method being by testing the lamps and globes under actual working conditions (see Curve III.).

At this stage, while discussing highly illuminated streets and the use

* *Illuminating Engineer*, vol. 1, p. 719, 1908.



Curve I.

Profile curves of candle-power of various vertical carbon flame lamps. The Jandus and Blondel A.E.G. are long burning lamps.

These curves are taken from figures issued by the manufacturers, but are chosen from lamps taking approximately the same watts and having opalescent or similar globes.

Curve II.

Candle-power at various angles of flame arc lamps, showing effect of dioptric and other globes.

These are the results of several photometric measurements made by the author in Regent Street, Oxford Circus, and Oxford Street.

It should be noted that the lamps in Regent Street, with the dioptric and clear globes, are taking 12 amperes, whereas the others are 10-ampere lamps.

of high candle-power units of light, the relative results obtained by the use of high-pressure gas lamps is of interest. Therefore I will again refer to the tests by Mr. J. T. Morris, from which he draws the conclusion that the candle-power of a high-pressure gas lamp varies 50 per cent., depending on the quality and pressure of the gas. His figures show that from 30 to 34 c.p. per cubic foot of gas consumed per hour is a very average result—this is when working at a pressure of 4 in. of mercury. As my own tests tend to corroborate this, I will take as an example a nominal 1,500-c.p. Keith lamp, which gave on test between

TABLE I.

Candle-power per Watt of Various Lamps at 10° to 15° from Horizontal.

Type of Lamp.	Watts per Lamp.	Candle-power per Watt.	Type of Globe.
Tungsten ...	From 40 upwards	0·8	Clear glass
Grouped Tungsten Lamps ...	300	1·5	In specially designed fittings
Open arc ...	500	0·7	Standard opalescent
Enclosed arc, direct current ...	460	0·5	Clear inner and outer globe
Excello flame arc ...	460	2·4	Standard opalescent
Excello flame arc ...	460	3·7	Dioptric and opalescent
Excello flame arc ...	550	6·5	Dioptric and clear
Jandus Regeneration	360 to 460	5 to 8	Standard globes
Magazine lamp ...	350	2·0	Standard globes
Magazine alternating	440	1·6	Standard globes

720 and 780 c.p. with a consumption of 23 cub. ft. per hour. This, when compared with a flame arc lamp giving 5 c.p. per watt at 1d. per unit, would have to be supplied with gas at 7d. per 1,000 cub. ft. in order to produce the same light for an equal cost, and thus it is obvious that even high-pressure gas lamps do not compare favourably in cost with those high candle-power electric arc lamps, which embody the improvements of the last few years.

At the beginning of this paper I referred to the early days of electric lighting, when the open-type arc lamp was the most efficient lamp available, and was therefore erected in considerable numbers for lighting the more important thoroughfares. This was the case in two

districts bordering on Marylebone, in each of which nearly 1,000 of these lamps were erected, and are still in use. In one of these districts where they are supplied from the mains of an Electric Supply Company they are spread over nearly 25 miles of streets, the cost per mile of lighting being about £880, and the minimum illumination resulting in this case being 0·05 c. ft. On referring to the Marylebone figures, where the same class of street is illuminated by means of the tungsten lamps, it will be found that a minimum illumination of 0·08 c. ft., nearly half as much again, is obtained at a cost of £414 per mile, or less than half. In the other neighbouring district the arc lamps are spread over nearly 37 miles of streets, and are arranged to give two different degrees of minimum illumination, namely, in the important thoroughfares 0·012 c. ft., and 0·008 in the lesser thoroughfares; at the prices charged this works out at about £450 and £350 per mile respectively. Comparing this with Marylebone, where the illumination even of the side streets is more than double the first, and sometimes triple, the cost does not exceed £204 per mile.

These examples are sufficient to show that, with the exception of very important streets, the tungsten lamp will give a better result at lower cost than the ordinary open type of arc lamps; but, of course, where the arc lamp has been used in the past, and the question of improving the illumination and of reducing the cost is under consideration, it would be unwise to incur fresh capital charges by replacing the existing arc lamps with a large number of small posts and fittings, and therefore I propose to call your attention to Croydon, where this problem has been most successfully dealt with. The borough electrical engineer, realising that certain classes of road were not of sufficient importance to require that higher degree of illumination obtainable by the use of flame arc lamps, decided to try the experiment of using groups of tungsten lamps contained in one lantern fixed as high as possible from the ground. The improvement in the evenness of the illumination was very noticeable, and the new form of lighting was generally approved. It was found that a group of three 100-watt Osram lamps contained in a suitably designed and constructed lantern mentioned in Table I., and of which the profile curve of lighting (IV.) is given on page 36, when erected 20 to 23 ft. above the ground gave a much better minimum and much more even illumination than the arc lamps, with the result that nearly 10 miles of road have already been converted to this system of lighting. These lanterns, which were the outcome of a considerable number of experiments and tests, carried out by the engineer and his assistants in conjunction with the writer, are designed to embody the same principles as the Marylebone fitting, namely, to have a larger area of white reflecting surface in very close proximity to the incandescent metal of the lamp, with the object of making the source of light appear large so as not to strain the eye in any way. And owing to the height at which these lamps are erected this white surface can be, and is designed to act as an efficient reflector, and

does considerably improve the distribution of light by nearly doubling the candle-power at 10° to 20° from the horizontal as will be seen from Curve IV., which compares the distribution from tungsten lamps fitted in these lanterns with that of an open-type arc lamp. The illuminating results are as follows, these lamps being 73 yards apart and from 20 to 23 ft. high. The minimum direct illumination is 0·041 when using the tungsten group lantern, against to 0·024 when using the 10-ampere open-type arc lamp. The cost per mile works out at approximately £200 per annum, thus a minimum illumination double that of arc lamps is obtained, and at slightly over half the cost. It is interesting to note that when these roads were lighted by gas mantles the minimum direct illumination was 0·0036,* and thus the illumination is now about seven times as high, the cost being about three times greater.

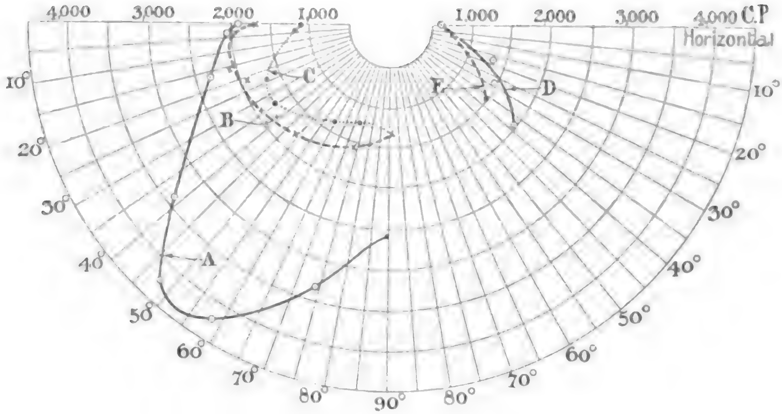
As in many towns the open-type arc lamps have been installed on a series system, it would necessitate considerable expenditure of capital to replace them by the more efficient grouped tungsten lamps if the mains had to be disturbed in order to put in a parallel system of cables, moreover individual switching then becomes necessary, which slightly increases the cost. In order to overcome these difficulties the author has devised a combined lantern and cut-out which permits of the arc lamp being replaced by a group of tungsten lamps, of which one is a spare lamp placed in a conspicuous position in the globe, and comes into operation in the event of any of the other lamps failing. The usual construction of these lanterns is as follows. The lamps nominally in circuit are placed round in a circle and are each connected in parallel through the winding of an electromagnet to the series mains. The spare lamp is placed in centre of the group at a lower level, and is connected through a contact operated by the electromagnet to the series mains. The electromagnet is so wound that when the normal lamps are lighted, and the current is passing through the coils in series with them, the magnet is not excited, but, in the event of a lamp failing, the balance of the ampere-turns is upset, and thus the magnet excited attracts its armature and connects the spare lamp. The advantage of this arrangement is that the automatic cut-in only operates in case of failure of a lamp, thus the contact is rarely made, and the circuit is never broken at the points of contact.

Among other examples of the great improvement possible with modern electric lamps, I would like to mention Harrogate, where the engineer, Mr. Wilkinson, has replaced the arc lanps by four 100-c.p. tungsten lamps, arranged on spreading arms at a considerable height, the result being excellent both as regards illumination and appearance.† It is interesting to note that at Harrogate the lamps are used without globes, but are provided with prismatic reflectors, which leads up to the question of reflectors generally. It is important that the reflectors should be designed with the object of reducing the effect of "glare," in other words, counteracting the high intrinsic brilliancy of the light

* *Journal of the Institution of Electrical Engineers*, vol. 36, p. 188, 1905–6.
† Ibid., vol. 44, p. 509, 1910.

source. For example, various samples of street lamps and fittings are often installed for inspection of councils and committees, and the writer finds that they invariably turn to him and point out as the fitting giving the most light the one which he has designed with the object of eliminating as much as possible the effect of glare, although very often the illumination derived from the lamp in that particular fitting is no better than the others, but to use an expression which I believe was invented by Mr. Mordey, the seeing capacity is improved owing to the iris of the eye remaining open. Thus it will be seen that a specification that relies only on candle-power or illumination does not always result in the greatest satisfaction to the public. There are many ways of reducing the deleterious effect of high intrinsic brilliancy of light sources, without interfering with the efficiency of the light. In Marylebone, for instance, it is done by the wedge-shaped white surfaces above the lamps being brought down as near the filament or light source as possible. A very ingenious method has lately been invented by Mr. Pragnall, based on the principle that nearly all light sources cover an appreciable area; thus by fixing thin sheets of metal having white surfaces, adjacent and radially to the light source, it is seen in the midst of an illuminated white surface, and not against the dark sky or distant surroundings, while at the same time practically no light is lost owing to the surfaces being thin and radial to the lamp. With arc lamps opalescent globes are very generally used to get over the effect of glare, but the greatest care is necessary in selecting these, as the loss of light is very often a serious matter. This is clearly demonstrated by Curve III. This curve is plotted from tests taken by the author under normal working conditions in the open, and it is interesting to note that the opalescent globe B did not seriously reduce the candle-power of the lamp at the important angles, namely, 10° to 15°, whereas C reduced it considerably.

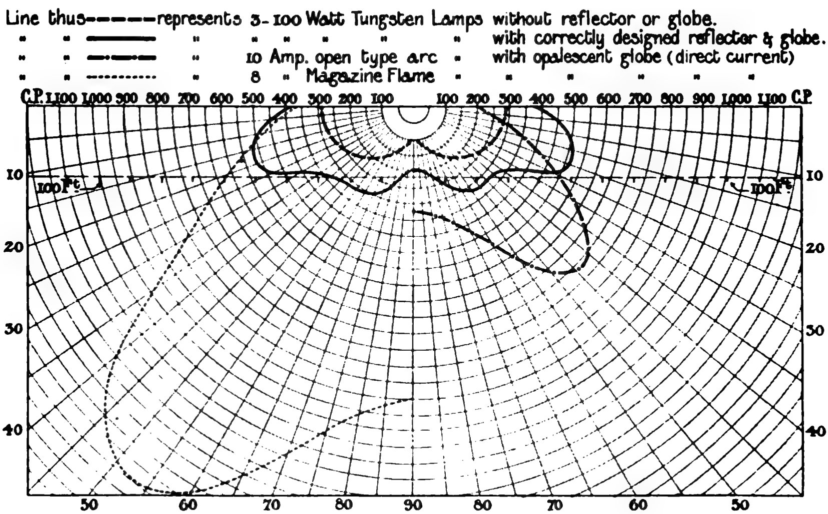
Some very interesting work has lately been carried out in the City of Westminster in connection with street lighting by gas, and as at the time of writing the lighting of Victoria Street has been completed, the writer has had an opportunity of measuring the illumination and judging the effect of what may be taken as the most modern form of gas lighting. It is not proposed to enter upon any criticism of the local authorities' action in accepting the tender of the gas company, but only to compare the results now obtained with those which existed in the past and those which could have been obtained by other units of light which were tendered for by the Gas Company. Before going into these figures, it is necessary to examine that part of the Specification relating to candle-power, under which the Electric Light and Gas Companies tendered. This is somewhat unique, reading as follows: "The candle-power shall be arrived at by taking the average of two sets of readings in any position with regard to the light under test—one set at an angle of 20° and a second set at an angle of 50° to the horizontal." It will be noted that there is no statement that the 20° ray shall bear any definite ratio to the 50° ray. Mr. Jacques Abady,



CURVE III.

Measurements made by the author on Beck flame lamps, taking 8 and 10 amperes respectively, and tested with various globes. The effect of the increased current is very noticeable, also the quantity of light absorbed by the opalescent type of globe.

A. 10-ampere lamp with clear globe.
B. 10-ampere lamp with opalescent globe, sample 1.
C. 10-ampere lamp with opalescent globe, sample 2.
D. 8-ampere lamp with clear globe.
E. 8-ampere lamp with opalescent globe.



CURVE IV.

The horizontal dotted line shows position of pavement to light angles for lamp 20 ft. high.

Note that the tungsten lamps with reflector give higher illumination than the open arc at any distance exceeding 50 ft., than the flame arc at any distance exceeding 120 ft.

[These curves are plotted from measurements made in the street.]

referring to this in his paper on the subject read before the Institution of Gas Engineers, states: "Of course it might be possible for an enterprising individual to make a lamp giving 180 candles at 50° and none elsewhere; and this would be a 90-candle lamp." But a lamp such as this would not comply with the general specification of the Westminster testing clause, and the example is stated simply as a reduction *ad absurdum*." Be this as it may, surely a clause stating what ratio the one ray should bear to the other was necessary, as any individual might have taken advantage of this clause and tendered for converging flame arc lamps with clear glass globes, or direct-current open-type arc lamps, which at 50° give from three to five times more candle-power than is obtained at 20°; the use of such lamps as these would naturally have resulted in a very low minimum illumination. As it is the high-pressure gas lamps installed give about 1·5 times more candle-power on the 20° ray than on the 50° ray, which is, of course, a ratio in the right direction, but not sufficiently so to prevent the illumination adjacent to the post being 20 times that of the minimum illumination, whereas with the small gas units displaced it was only 16 times as great, and if the height of the small units had been that of the present units it would only have been twice as great, which would have come under the head of even illumination.

The units of light according to the specification were to be 90 c.p., 180 c.p., 300 c.p., 1,800 c.p., 3,000 c.p., for which the accepted gas company's tender works out at £2 16s. 6d., £4 10s., £6 10s., £15 10s., and £22 per annum respectively. Of these the 1,800-c.p. unit fixed 20 ft. high was selected for Victoria Street. This street is approximately 3,600 ft. long, and 25 such units have been erected in place of 50 upright double incandescent gas mantles placed 12 ft. from the ground, with the result that the minimum illumination has been increased to 0·15 c.p.

The cost of public lighting by electricity naturally depends on three factors:—

1. Cost of electrical energy.
2. Cost of lamp maintenance (lamps or carbons burning, cleaning, lighting, repairs, etc.).
3. Capital charges and repayment of same.

Item (1) will apply to every type of electric lamp in proportion to the energy it takes, and as opinions vary as to the right charge to make for electrical energy when used in public lamps, I propose to consider this item from a consumer's point of view, arguing that it can make no difference to an electricity supply authority for what purpose it supplies the energy, excepting only that in the case of street lighting a certain amount of credit should be given on account of the advertisement.

All-night street lighting has a load factor of 40 per cent. It is true that it overlaps the peak of the ordinary lighting load, but, on the other hand, it helps to fill up the depression which occurs in the load curve

of nearly every station between midnight and sunrise; therefore, as a consumer, it has more value than a power load consisting of motors used during ordinary factory hours. On this score alone it should rank as better than a motor load and be charged less, in which case the large number of electricity undertakings which are supplying power at 1d. per unit for motors can well afford to supply the public lighting at less than that rate, and it is very rarely that the big supply companies or large municipal undertakings ask more than that sum, which they find pays them, as it results in a profit on their generating costs and also covers the cost of repayment of capital in services, etc. The latter should be spread over at least ten years, for there is little doubt that when once the electricity department has obtained the street lighting it will retain it.

In the smaller undertakings where generating costs are proportionately higher, the price of 1d. per unit would appear low. In this case I think a good way of dealing with it is that described by Messrs. Handcock and Dykes, in their paper read before this Institution in November last, namely, to take the standing charges per kilowatt of consumers' demand, which, in the example given, stood at £17, and for a 60-watt lamp would work out at—

$$\frac{£17 \times 20 \times 60}{1{,}000} = 20\text{s. per lamp per annum.}$$

Taking the running charges at 0·4d. and the hours of burning as 4,000 per annum, this works out at—

$$\frac{4{,}000 \times 60 \times 0{\cdot}4}{1{,}000} = 96\text{d.},$$

making a total charge of 28s. per lamp per annum, which works out at the rate of—

$$\frac{28\text{s.} \times 12}{240 \text{ units}} = 1{\cdot}4\text{d. per unit.}$$

Thus, treating the street lamps as an ordinary consumer, a remunerative price per unit may be taken as 1d. for large undertakings and 1·5d. for small undertakings, which includes, as in the case of consumers, the cost of service to the ordinary distributors, but not of fittings, etc., which would come under the same heading as the consumers' wiring and fittings, which are part of the installation. It will be noted that even with this rate of charge the revenue per 60-watt lamp is nearly eight times the average revenue derived from lamps installed in consumers' premises, and moreover, as no meters need be installed and the cost of the services is low compared to that for ordinary consumers, all meter-reading charges are dispensed with and the clerical and office charges are practically nil.

The cost of lamp maintenances must again be divided between two different classes of lamps, namely, incandescent and arc lamps; and as it is essential to know the cost per candle-power per annum in order

to ascertain the most economical lamps to use for the purpose and the best method of arranging them, it is necessary to come to some approximate estimate of this figure. With tungsten lamps the cost of lamp renewals at the present price of lamps depends largely on the candle-power and slightly upon the volts, but the following figures which are based on a considerable experience in various towns will act as a guide to the likely maximum, including rates of renewing :—

TABLE II.

Cost of Tungsten Lamp Renewals.

Total Candle-power of Unit.	Cost per Annum (4,000 Hours).	Cost per Candle-power per Annum. Naked Lamp.	Cost per Candle-power per Annum in Special Lantern.
	s.	d.	d.
50	8	2·4	1·3
100	13	1·8	1·2
200	20	1·2	1·0
300	30	1·2	1·0
400	40	1·2	0·8
500	50	1·2	0·6

The cost of lighting, extinguishing, cleaning, and repairs depends largely on the system of supply, whether from the distributors and separately switched, or from special street-lighting mains, but it will be found that the interest and sinking fund on special street-lighting mains is about equal to the cost of individual switching, and therefore the latter system is likely to be largely adopted, in which case the cost per post may be taken as 16s. per annum, this being constant whatever the candle-power of the lamp. The total cost per candle-power works out as shown in Table III.

The capital charges of electric street lamps, of course, depend upon the value of the posts and lanterns; the cost of the service, etc., being put roughly, they may be taken as follows :—

	£
Light units up to 200 c.p. (tungsten) erected 12 ft. high ...	3
Light units up to 500 c.p. (tungsten) erected 16 ft. high ...	5
Light units above 500 c.p. (arc lamps) erected 20 ft. high ...	20

The cost of maintaining arc lamps, including carbons, trimming, repairs, lighting, and extinguishing, varies very much with the type of lamp, the enclosed or regenerative type of lamp naturally being the

lowest, flame arc lamps burning a good quality of carbon being the highest. In the following estimate it is taken that one man can attend

TABLE III.

Cost of Lighting, Extinguishing, etc.

Total Candle-power of Unit.	Cost of Lighting, Extinguishing, etc., per Candle-power per Annum.
	d.
50	4·00
100	2·00
200	1·00
300	0·66
400	0·50
500	0·40

(Calculated without reflectors.)

to 130 enclosed or regenerative-type lamps and 70 open-type lamps; the cost per annum works out approximately as shown in Table IV.

These results will, of course, vary with the local circumstances,

TABLE IV.

Cost of Arc Lamp Carbons, Trimming, etc.

Size of Light Unit.	Cost per Annum.	Cost per Candle-power per Annum.
	£ s. d.	d.
300 c.p. unit (open type)	4 10 0	3·6
1,000 c.p. unit (flame arc dioptric globe and opalescent outer) ...	8 0 0	2·0
3,000 c.p. unit (flame clear outer) ...	8 0 0	0·7
2,000 to 4,000 c.p. unit (regenerative flame)	2 10 0	0·3 to 0·15

cost of labour, etc., but can be taken as a very general guide. Adding together the previous figures we get the total cost per candle-power

per annum exclusive of capital charges, this table including cost of current taken at 1d. per unit.

TABLE V.

Total Cost per Candle-power per Annum.

	Candle-power of Light Unit.	Cost per Candle-power per Annum (Total). Naked Lamp.	Cost per Candle-power per Annum in Special Lantern.
		d.	d.
A	50 tungsten	10·50	7·0
A	100 tungsten	8·20	5·0
A	200 tungsten	7·00	4·3
A	300 tungsten...	6·66	4·1
A	400 tungsten	6·50	3·8
A	500 tungsten	6·40	3·5
B	300 open arc	10·20	—
C	1,000 flame arc	3·65	—
C	3,000 flame arc (dioptric and clear outer)	1·32	—
D	2,000 to 4,000 regenerative flame	1·0 to 0·8	—

Having obtained an approximate table of costs per candle-power per annum for various units of light, it is easy to ascertain which are the best to use under different circumstances. For this reason I have given on page 42 in Table VI. the total candle-power necessary to produce a minimum of illumination (horizontal) of 0·1 c. ft. with lamps spaced at different distances and also at two different heights—namely, 20 and 12 ft.

From Table VI. two important features are very noticeable, namely, the large reduction in total candle-power necessary to produce the same minimum degree of illumination with small units of light placed close together, and the effect of height of the lamps on horizontal illumination; this latter point will be dealt with later. It will be noticed that when the lamps are spaced at 30 yards only one-ninth of the total candle-power is necessary to give the same result as when they are placed 100 yards apart; therefore from the table of costs per candle-power it will be seen that unless a lamp giving a very high

candle-power at low cost be used, the closer spacing would be the cheaper alternative. Again, converging flame lamps (unless provided with dioptric globes) when erected at 70 yards give illumination at the same cost, equal to small units of light placed between 40 and 50 yards apart, provided, of course, the small units of light are fixed at the same height.

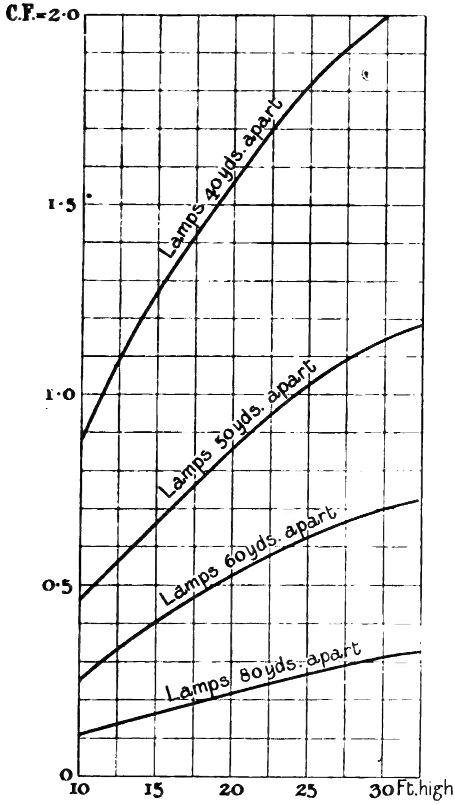
With reference to the height of lamps, according to Curve VI., based on horizontal illumination, and obviously in order to obtain even illumination, they should be placed as high as possible; for instance, in Baker Street, if the lamps had been 20 ft. high the minimum horizontal illumination on the ground would have been 0·11 c.p. instead of 0·08, or an increase of nearly 50 per cent.; but I doubt whether the lighting committee or the public would agree that the illumination of the street had been improved 50 per cent., and am certain that there would be no hesitation in their choice between increasing the height of the lamps 8 ft. or increasing the candle-power 50 per cent., provided the increased candle-power cost no more. This, to my mind, demonstrates clearly one of the objections to horizontal illumination as the gauge of street lighting, for the increase in the height of the lamps would not in any way increase the illumination of pedestrians and vehicles or other vertical objects, and it is certainly misleading owing to the introduction of the cosine factor. On the other hand, the specifying of minimum horizontal illumination does encourage raising

TABLE VI.

Candle-power necessary to obtain Minimum Illumination 0·1 *c. ft.*

Space between Lamps.	Candle-power of Lamps.		Total Candle-power per Mile.	
	12 ft. high.	20 ft. high.	12 ft. high.	20 ft. high.
Yards. 100	—	8,800	—	156,000
90	—	6,300	—	125,000
80	7,300	4,539	160,000	100,000
70	4,800	3,060	121,000	76,600
60	3,140	1,950	92,000	57,000
50	1,820	1,186	63,500	41,600
40	950	620	41,500	27,300
30	400	300	23,300	17,600

the height of the lamps, but, as I have mentioned in previous writings, the factor of direct illumination covers this point when the maximum and minimum are stated. That the difference between the maximum and minimum illumination at any point of a street should be as small as possible is so important that it is gratifying to note the comparatively



CURVE V.

Variation in horizontal illumination due to various heights of lamps. The curve is calculated on the basis that the lamps are giving equal candle-power at all hemispherical angles. It demonstrates clearly the effect of the cosine factor if horizontal illumination is used for comparison purposes.

low candle-power when measured near the vertical of the tungsten and modern arc lamps, especially when the former are in correctly designed lanterns. For example, maximum illumination with the inclined carbon flame lamps is as high as 10 c. ft. in Oxford Street, with a minimum of 0·11 c. ft., or a diversity factor of 90. In Baker

Street the maximum illumination on the ground is 0·5 c. ft. with a minimum of 0·08, a diversity factor of only 6. Again, in Regent Street, where Excello lamps having dioptric globes are in use, the maximum illumination does not exceed 3 c. ft., the minimum being 0·23 c. ft., or a diversity factor of 13.

The importance of correct characteristic light distribution is clearly brought out in Curve VI., where the candle-power at various downward angles necessary to produce even illumination is compared with the candle-power given at those angles by: (A) Tungsten lamps with a suitable reflector, such as the Marylebone type, which it will be noticed fairly closely approaches the correct curve. (B) A vertical low-pressure gas mantle which gives about the same curve as a tungsten lamp without a reflector. (C) A low-pressure inverted gas mantle.

The effect of using correctly distributed light is not only more even illumination, but also reduced cost of lighting for a given minimum, which is seen by the following comparisons :—

Position.	Minimum Illumination.	Diversity Factor.	Cost per Mile per Annum.
			£
Baker Street (Electric)	0·08	6	356
Regent Street (Electric)	0·23	13	660
Victoria Street (high-pressure gas) ...	0·15	20	540

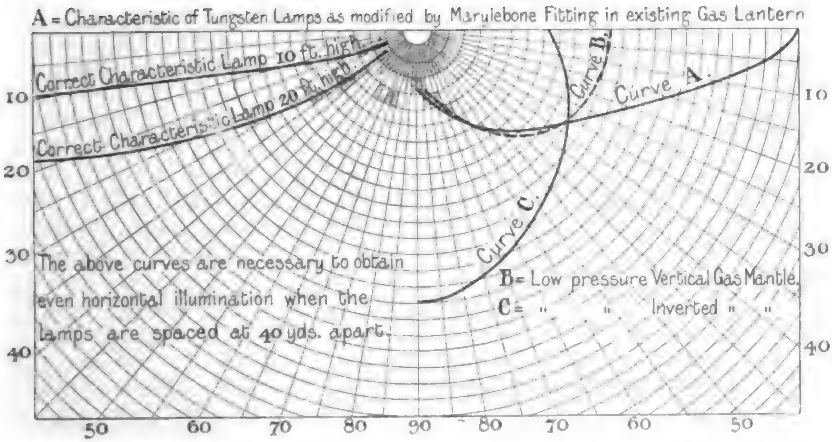
NOTE.—The tender for the Regent Street type of lighting was subsequently reduced to £425 per mile per annum.

The above figures call attention to the considerable variation in the diversity factor of illumination. The importance of this factor cannot be over-rated. A. J. Sweet * states that a ratio of maximum to minimum (illumination) of 4 to 1 is permissible, and points out that the present factor more frequently falls between 100 to 1, or even 500 to 1. For example, in Oxford Street, using flame arc lamps, it is 99 to 1; whereas in Regent Street, where the same type of lamp was used, but with a dioptric globe, this was reduced to 13 to 1. In Victoria Street, the latest example of gas lighting, it is 20 to 1; whereas in the important streets of Marylebone it is 6 to 1. In both Regent Street and Marylebone this great advance was brought about by the correct use of globes and reflectors specially designed for the purpose. It is the possibility of using such globes and reflectors with electric lamps which gives them a great advantage over gas, where the dissipation of the great heat neces-

* *Journal of the Franklin Institute*, vol. 169, p. 359, 1910.

sary for the efficient use of mantles makes the use of efficient globes and reflectors a practical impossibility.

For instance, in Victoria Street the light rays from the high-pressure gas lamps which reach the point of minimum illumination are only 1·5 times the power of those adjacent to the lamp-post. In the case of the tungsten lamps in Marylebone, they are six times the power—hence the more even illumination. It is interesting to note that if the latter lamps had been placed a few feet higher, and spaced at, say, 100 posts to the mile, the illumination would have been even throughout the street with a diversity factor of unity. At first sight this would appear considerably to increase the cost, but this is not so, as the candle-power of the lamps could be reduced to one-fifth without reducing the illumination.



CURVE VI.

I must apologise if I have repeated too often examples and figures proving that the multiplicity of small-light units results in more efficient street lighting; but the fact that measurements and figures invariably lead to this conclusion proves that it is worthy of the consideration of those who have to deal with street-lighting problems.

I am aware that the average man who is asked to compare brilliant and powerful lamps with the less brilliant but increased number of light sources will generally vote in favour of the powerful light, regardless of the result; but the fact that the Marylebone lighting has given satisfaction to all concerned does prove that in the long run even illumination is appreciated.

The eyesight of the present generation is suffering from the indiscriminate use of large glaring light units, unsuitably placed. Therefore it is important that those who are called upon to illuminate streets, where the minimum illumination cannot exceed 0·1 of a candle-foot,

should not be tempted to accentuate this low figure by producing a few patches of bright light.

It is noticeable that in the past the small-light units derived from gas have been more economical for outdoor lighting than those produced by electricity. The reverse is now the case, therefore electrical engineers should be able to compete favourably, considering that the light they are able to supply is constant, reliable, capable of correct distribution, and easily manipulated, which must result in its adoption for exterior lighting in the same way as it has been so generally adopted for interior lighting.

There is one other feature which I should like to take this opportunity of bringing to your notice, namely, the rating of light units.

It is the custom with incandescent electric lamps to mark them with the mean horizontal candle-power, and they are known by that figure ; but if by the use of suitable reflectors or globes this figure is often more than doubled over the angles where the light is required, that unit becomes of twice the value. You will notice that in completing this paper difficulty of this sort has arisen, and that in calculating the cost per candle-power the writer has in most cases given the figures as based on the horizontal candle-power of the naked tungsten lamp; whereas, where they have been erected in suitable lanterns or globes, this cost per candle-power-hour is reduced to a half or a third. This must be carefully borne in mind when using the tables referred to.

Before concluding I would like to thank the many municipal and other engineers who have so kindly sent me data which has helped to compile the figures I have placed before you. I am sure you will agree that by the use of modern electric lamps the lighting of our streets and thoroughfares can be carried out both economically and efficiently, and that no electrical engineer need hesitate to tender for this class of work, knowing that, should he obtain it, his undertaking will earn both money and credit, provided that the results are justly and scientifically compared with those of his competitors.

I should like to take this opportunity of warning engineers that good illumination, though the prime object in street lighting, is not the only feature to be considered. Careful thought must be given to obtaining as even illumination as possible ; and if high intrinsic brilliancy is carefully avoided the result will be in every way satisfactory, not only to the lighting authorities, but also to the general public.

DISCUSSION.

Mr. Bailey. Mr. FRANK BAILEY: The subject of this paper is of great interest to the majority of the members of this Institution, whether they are engaged in the manufacture of plant or in the equally important duty of carrying out the public supply of electrical energy. I think we must

all agree that the author of this valuable paper has put before us many results of great interest. It is a paper which enjoys the unique position most worthily of being the first paper placed before us for discussion in the first session of our new abode. Taking the title of the paper, "Street Lighting by Modern Electric Lamps," I think the author has undertaken a somewhat large order. Many of us would like to say that the first duty in lighting streets is not to find out how much illumination can be done for the least cost, but how much illumination people require. The author has proved his case in applying in many cases the tungsten lamp and in producing most valuable results at Marylebone at a cost which amply justifies itself and competes worthily with all other methods of illumination. It is our duty to draw the attention of the authorities and the people themselves to the very unsatisfactory nature of most of our street lighting. It is not how little they can do with, but how much they ought to have. We are now satisfied apparently with street lighting giving an illumination not very much more than we had many years ago before the conditions were entirely altered. If we consider for a moment what those conditions are, we need only think of the enormous development of motor traction and the development of petrol-propelled vehicles in the street. We have seen the speed of street traffic increase enormously in the last four or five years, and yet the illumination of the thoroughfares remains much as it used to be a good many years ago. Surely that is not the sort of thing we ought to be content with. We ought to feel gratified that the author has devoted so much energy to this problem, and hope that not only the various authorities in London, but those in the country, will see fit to employ the services of an expert adviser, in order that he may draw up an intelligent specification, telling the people what they ought to have and not what they think they ought to have. One sometimes comes across weird specifications for street lighting, so worded as to make evasion possible with the greatest ease. But that is not the policy of the electrical engineer of to-day, even when he sees a very weak specification. I have always found that he is the man to draw attention to the inaccuracies of the specification and to put them right in practice. But in the present case we can only deplore the gloomy look of all our thoroughfares, and think how very much better we could do the lighting if only we were allowed to try. That has been very much my position in the City of London within recent years. We have had to ask to be allowed to try; we have had to beg of them to allow us to show what we could do with modern appliances in order to bring up the street illumination to a pitch where people could see definitely. We all know perfectly well that efficient lighting is a matter of life and death in many thoroughfares. Owing to the speed of modern motor vehicles, there is hardly time for pedestrians to get out of their way if it is needful for them to do so. The pedestrian can see the motor, but the man driving the motor cannot see the pedestrian. We are told that the foot-passenger has to be taken care of; in other words, that the Mr. Bailey.

Mr. Bailey. road traffic should look after him; but I do not see how that can be done when vehicles find it necessary to carry a light and there is no law compelling a pedestrian to carry his own lamp. I thought, on leaving this hall after the Presidential Address a fortnight ago, that all of us going along the Embankment ought to have carried our own lights in our hands in attempting to cross to the other side of the Embankment. The traffic is great, the lighting is poor, and if all of us had carried one candle, 500 people perambulating round the Embankment with candles would have given a better illumination than the present arc lamps do. It is not right that such a state of affairs should exist. The author in this paper might justly have drawn attention to the fact that street lighting is not carried out universally as it might be, and that by the aid of modern lamps, whether arc lamps, incandescent lamps, or any other kind, we ought to be able to show, and can show, a much better result at the old price. We can show results creditable to this country and to this city, if only we had a little more money to do it with. This is not a case in which we ought to see how much light we can give for the least amount of money, but how much light the people ought to have and at what cost; that has been my mission in attempting to light Cheapside in the manner in which it ought to be lighted. The standard of illumination should not be less than that we now obtain in Cheapside by using ten arc lamps suspended at intervals of about 30 yards over the centre of the road, by means of which not only can street traffic be carried on safely, but pedestrians find their way without carrying a candle. Another reason why I most strongly urge that all electrical engineers should devote their attention to teaching the authorities how to conduct that part of the work, is that better lighting must mean fewer police, therefore less cost and fewer burglaries. That has been shown over and over again, where the police in a wide thoroughfare can look down it, see all the places, see if there are any men lurking about, and what they are doing. The inspectors of police would also be able to see the constables on duty, because they could not be hiding in the shadows, as there would not be any shadows for them to hide in. I suggest that the attention of electric lighting authorities should be devoted, not to giving the old standard at lower cost, but to obtaining increased illumination at an equivalent price. The people must have more light, and I think we ought to supply it.

The author very rightly mentions the question of price. Being more or less commercial, I think we must all feel that in justifying lighting at the cost he has mentioned he has done us a good service. He mentions 1d. per unit as being the average price. I am not quite clear how he arrived at that figure. He might have taken 4d. and said that that is a good price—perhaps that is too much; and he might have taken four units a 1d., which I fear would be dependent on the progress of the inventive genius of our President. But in taking 1d., it is perhaps a fair, good, average price, and I do not think it is one we should quarrel with. The results obtained with

that 1d. worthily, I think, emphasise the use of metallic filaments in streets of minor importance. But if I may go back to the main thoroughfares, I do not see myself that it is wise or necessary for us to urge the application of tungsten lamps for lighting of such importance as can only be properly carried out by flame arc lamps of high candle-power. I put Cheapside before you as an example of what should be done in main thoroughfares, and there are plenty of main thoroughfares in London which justify that expenditure of money, which works out at something like £800 a mile. That does not appear to be an excessive sum to be paid for what is absolutely required for the protection of both life and property. So far as our work in the City has gone, we have to acknowledge with feelings of gratitude the assistance the author has rendered to us in many of the fittings we have employed. It may seem a small thing to devise a fitting for a simple matter like street lighting, but when we try to carry out experiments and then obtain the special goods afterwards, it is by no means an easy or simple operation within the time available. Not only has the author worked out the details so admirably regarding reflection and the proper form of globe to be adopted, but he has shown us how to obtain the articles with the least possible delay in time. It may be suggested that it would be better for any man who devotes his time to expert knowledge not to make his own fittings and put them on the market; but I feel we owe a debt of gratitude to the author for having done both at the present time. He has now shown us what to do, where to get it, and how to get it in time. As time goes on it will become part of the ordinary commercial trade of the country, and then we shall be only too thankful to know that the author is ready and willing to undertake the duties of an expert adviser in this important matter. Mr. Bailey.

Mr. CHARLES P. SPARKS: The author has drawn our attention to the importance of the specification relating to candle-power. In some cases the average of the candle-power at two angles—selected at random—is taken without specifying that the illumination at these angles must bear some definite ratio to one another; again, the importance of the ratio of maximum to minimum illumination is ignored. The basis of these specifications generally comes from our competitors, the gas companies, who have served a long apprenticeship in the public lighting business. Comparatively speaking, we are new to the street-lighting industry, and I think this Institution would do a great public service by appointing a Committee which would draw up a standard specification for street lighting. While the specification might not be adopted in all cases, it would at least act as guide and could be taken as an authoritative basis. The specification should be drawn up on broad lines, taking into consideration not only the electrical and gas interests, but also what is wanted in the public interest. As pointed out by the author, until recently we have been very much handicapped in this industry by the fact that we had only large units of light, and the method of distributing the light resulted in points of maximum illumination, which gave a very big diversity factor; although the Mr. Sparks.

Mr. Sparks. public may require educating to the use of a new standard, the old method is not the standard of lighting required; we require a low diversity factor, even if the standard of illumination remains low. I am certain that the author's remarks, pointing out the desirability of using proper methods to get this low diversity factor, are of great importance, not only to the electrical trade, but also to the public. I wish to endorse Mr. Bailey's remarks with regard to the assistance those in the supply business have received from Mr. Harrison. Until recently all the pioneer work in connection with the lighting of public streets has been done by the gas companies. Mr. Harrison has devoted himself for some years past to the subject, and not only is he up to date in every way with regard to the methods of lighting, but also in regard to the way in which the present burners should be used. With regard to the existing electric lighting for public purposes, with the exception of isolated cases, it is almost entirely in the hands of those municipal authorities who themselves own the electric supply stations. They went into this business principally with the open or enclosed type of arc lamp, which compares most unfavourably with the new lamps to which the author has referred. I think the first duty of these undertakings is to try and bring themselves up to date. Go where one will, one is struck by the very poor comparison these old-type lamps bear to modern gas lighting, let alone modern electric lighting; seeing the rates at which most of these contracts have been taken, there is an ample margin to pull out the whole of the old fittings and put in modern ones, and for the credit of the electrical industry I hope this will be done at a very early date. Lastly, with regard to the price of energy, the author suggests that the basis in the smaller towns should be 1½d. a unit, and for the larger cities 1d. a unit. In view of the prices now quoted by our competitors, I look upon the figures given, especially of 1d. per unit for the larger cities, as being on the high side. I feel sure that, unless the supply undertakings are prepared to offer energy at a lower rate than is indicated in the paper, we shall not have much chance in open competition of wresting the bulk of the public lighting business from our competitors, the gas companies.

Mr. Seabrook. Mr. A. H. Seabrook: I feel that this paper will be a most useful addition to our files on street lighting. There is a welcome ring of conviction running right through the paper from beginning to end; it is so obviously written by a man who thoroughly understands his subject, and, what is of more importance, believes in his subject. Mr. Harrison is, of course, an enthusiast. If you want to know the candle-power of various gas or electric lamps in your area you have only to ring him up and he will spend half the night in discussing the matter with you. The figures given in the middle of page 25 of candle-powers on actual tests of 4½-ft. burners are rather striking, namely, an average of 50 c.p. and 76 c.p. as given by the testing authority "connected with the gas industry," and 45 c.p. and 76 c.p. as given by Mr. Harrison. If you compare the candle-powers in actual commercial use in the streets with the figures given as the correct figures by the gas companies you

will find a very striking difference indeed. I have underlined these words in the middle of the page in red : "I tested for my own satisfaction." If a few more of us would test for our own satisfaction and not take figures from advertisements we should not have the absurd disbelief in electricity for lighting, heating, and cooking which exists at the present time. We never have a commercial test from the gas people, you have to test for yourselves, and a gas-meter is one of the easiest things to test to enable you to get your own figures. Mr. Seabrook.

With regard to the price of energy charged in Marylebone for street lighting, 1d. has been suggested by Mr. Sparks as rather on the high side. Considering our street lighting people are saving about £2,000 a year, it seems to me to be unnecessary to go below 1·42d. We have to a certain extent to fix our price according to what the stuff will fetch (somewhat on Mr. Cowan's lines), and also base the price on that of our competitors. The question of loans mentioned on page 28 is a most important one. There is a great dislike on the part of the Local Government Board to sanction loans for services for street lighting. There are plenty of cases in which you could get £3 revenue per lamp for street lighting on a contract of from two to ten years, but you cannot get the loan for the expenditure, although you can get a loan to put a service in for a small consumer who pays you £2 a year and may go off at the end of six months. On page 30 the dioptric globe is mentioned. I have seen it in Regent Street, and it seems to me to give a very unpleasant glare. I have often stood at Oxford Circus and looked down Oxford Street and then along Regent Street. You can comfortably look at the lamps in Oxford Street, but it is not comfortable to look at the lamps in Regent Street, the glare is excessive.

I wish the author had made a few remarks about the question of side-walk columns as compared with centre lamps for arc lighting. I have come to the conclusion that where a street is wide enough for centre columns that is the best position to put the arc lamps, however high they are. If there be a suitable building on each side for rosettes and span wires, then the arc lamps give a very good effect suspended in the middle of the street. Arc lamps on the footpath waste an enormous amount of their light on the buildings which do not require the light, and if a street cannot be lighted by centrally supported arc lamps it seems to me much the best way out of the difficulty to employ a medium candle-power tungsten lamp.

Mr. W. A. VIGNOLES: This paper is specially interesting to us members from the provinces as showing that the whole of London is not reverting to gas lighting as our competitors in Grimsby would have us believe. At the time the Westminster contract was made and a few lamps were changed over to gas, all my Committee had newspapers sent to them marked with blue pencil, and came to me to know why London was throwing out electric light. This paper reminds us that quite the contrary is taking place in a great many districts in London. With reference to the Local Government Board's attitude towards loans for Mr. Vignoles.

Mr. Vignoles.

public lighting, we made application a short time ago for a loan for putting up electric tungsten lamps in place of the existing gas lamps. An inquiry was held, and after complete detailed estimates showing that we could make a profit on the prices to be charged, and that the town would not pay any more, had been submitted, the Local Government Board sanctioned the loan without any demur. The term of years fixed was ten for the posts and the fittings, and also for the services, although for services to ordinary consumers the term of years is fifteen, and used to be twenty-five. The conclusion I have come to is that the Local Government Board will sanction a scheme if it can be shown that it is a sound one and full details are supplied to them.

The next point I should like to touch on is Mr. Harrison's standard of illumination, and I must say that it seems to me questionable if the minimum horizontal illumination should be the only point considered. Surely in a street one would not put a Bradshaw on the pavement to try and read the figures, one would hold it up in a vertical direction so that the rays of light would fall upon it. In a street one wants to see the people moving about, and the rays of light striking a vertical surface would, I think, be a better standard to take. Then the minimum does not give sufficient information; it is quite conceivable that a street might be lighted uniformly from one end to another with a line of small lamps arranged to give the minimum mentioned by the author with a diversity factor, as he calls it, of unity. I do not think, however, that any one would consider a street lighted in this way to be as well lighted as if large flame lamps were arranged at intervals giving the same minimum in between the lamps, but with a much greater illumination nearer the posts. In the street lighted with the flame lamps it would be much easier to see anything moving at a distance than in the case mentioned with the uniform illumination from end to end. The other feature the author brings out in his paper is the immense advance that has been made in arc lighting by the invention of the enclosed flame arc lamp; both on the question of cost and on the question of candle-power it is far ahead of anything that has been done up to the present. Quite recently in Grimsby we took out the whole of the existing 12-ampere open-type arc lamps and substituted these enclosed flame arc lamps for them. The result is that we get five or six times the amount of light at a less cost. The cost works out at about £400 a mile for practically 4 miles of the principal streets, the lamps being 84 yards apart. The cost of the change, amounting to £700, was met out of revenue. The author makes many comparisons between tungsten lamps and old types of arc lamps, in all cases considering the minimum illumination only. This does not seem to me to be quite fair, as the tungsten lamp seems to be specially designed to give the illumination in the direction that Mr. Harrison wants it. I would suggest that a new lease of life might be given to some of the old open-type lamps if they were fitted with dioptric lenses, as this would bring the rays of light into the position

the author wants them, and by referring to Curve IV. it will be seen that the arc lamp would then compare very favourably with the tungsten fittings. As regards the cost of running the arcs, I agree generally with the figures that Mr. Harrison has given, and would only point out that the reason for the large saving with the enclosed flame lamps as compared with the open type is that the carbons cost considerably less per hour, while owing to the long burning hours the cost of labour is very much reduced. Mr. Vignoles.

Turning now to the tungsten lamps in use in Marylebone, I should like to ask why two lamps are fitted on every post. This may have been done so as to have one in reserve in case of failure, but of course it increases the cost of renewals. I should also like to know if there are any fuses except those at the top of the post. In Grimsby it was finally decided not to purchase the posts belonging to the Gas Company, as, unless we had depended solely on the fuses at the top of the posts, we should have had to build a pit in the pavement to contain a pair of cut-outs. The latter course was expensive, while the former was thought undesirable owing to the danger, if posts were knocked down, of a cable connected solid to the mains being cut. The result was we purchased new posts, with fuses in the base, and fittings, the latter taking the form of swan necks with an inverted reflecting cone over the lamp. On that particular point I might say that I think the author has made an excellent job of the alteration of the existing gas lamps at Marylebone, but after a great deal of consideration I have come to the conclusion that it is very difficult to design anything better than a lantern of this shape. When all is said and done, an electric lamp hung inside a gas lantern with four panes of glass and a white reflector kept nice and clean, is very hard to beat. In our town we have noticed that the same lamps arranged in pairs in a converted gas lantern look as if they were giving very much more candle-power than the same lamp hung under an inverted cone fitting. This is simply due to the reflection of the lamp in the glass and from the white top. That is a practical point which I think is well worth consideration. As regards the cost of the alterations, I see in Marylebone it amounted to £3 per post, which, I take it, includes the cost of the service and fitting up. This is, I think, a very fair figure. We have been doing it at something less in Grimsby where labour is probably cheaper, but of course we have had to bear in addition the cost of the new post, so that our total cost of post, fitting, wiring, and service amounts to something under £4 per post. As regards the cost of running, the figures given by the author seem to compare very favourably with what we have worked out, and the result is that the price received for energy in Grimsby comes to very much the same as in Marylebone. In Grimsby we are charging the same rate for the lamps as the Gas Company charged the Corporation for the gas lamps, and we have a nice margin, because 1d. per unit is quite a satisfactory figure for energy used for this purpose.

Mr. A. P. Trotter: There are three ways in which this subject may be studied: (1) By those in a laboratory, who can examine various Mr. Trotter.

Mr. Trotter, kinds of lamps with a photometer; (2) by those who can work in an armchair with a slide rule and tables, and make theoretical calculations; and (3) by those who can tell us all about the cost, and that is what comes home to the engineer. We value this paper largely because it is so full of information that we cannot get in the laboratory and cannot get with a slide rule, but which we can get from a practical man like the author. The cost is, after all, that which determines the success of engineering undertakings. The diversity coefficient is one to which the direction of engineers will have to be given, when they deal with illumination, as carefully as to the diversity factor of supply. I am not quite sure that I agree with Mr. Harrison when he speaks of that case of lighting in Baker Street, where if the lamps had been raised a little higher, the minimum illumination would have been raised and people would not have appreciated the light so much. That, I think, is because the lower diversity factor is appreciated more than the higher diversity factor. If we have a high diversity factor, a small illumination, and a uniform one, it is not as useful as if the same total quantity of light were distributed with a moderate diversity factor, with a good deal of illumination in certain places and less light—not enough to read a Bradshaw by, perhaps—in others. It does not strike one so at first. Thirty years ago I gave attention to this subject when arc lamps were coming in, and we could not make one burn satisfactorily with less than 9 amperes. There was a great deal of talk at that time about the subdivision of electric light, and the Swan lamp was hailed as a mode of sub-division of electric light. It seemed to me that the higher efficiency of an arc lamp as a light producer might be utilised by distributing the light instead of sub-dividing it, and at that time I invented what was known for some years as the Trotter dioptric globes. That fact has never been mentioned in this Institution, as far as I remember, during those thirty years till to-night. My dioptric globes have been forgotten by everybody. Naturally in an invention which was brought out twenty-eight years ago there was room for improvement during that time, and it has been improved. Most of us know the Holophane shades which are improvements in certain directions upon my own invention. I was trying to distribute the light, and these dioptric shades of Korting and Mathieson used by the Union Electric Company with Excello lamps are something like what I was doing. But mine were, I think, better, for I tried to avoid the glare spoken of, because I distributed the light horizontally as well as vertically. The mistake I made then was by trying to distribute the light strictly uniformly, which might have been done, but people did not want it. They want, I think, changes in their light. I think it is more convenient to have a moderate diversity factor, and that will be a very important question to decide in the economy of lighting, because, given a certain minimum and a certain diversity factor, there is a good deal to be worked out by the engineer. You might have lamps of $\frac{1}{2}$ c.p. placed, for example, 1 ft. high and 1 ft. apart, each giving a minimum horizontal illumination of $\frac{1}{10}$ of a foot-candle.

It sounds rather absurd, but I have seen lighting like that in the grounds of exhibitions. If this minimum of $\frac{1}{10}$ foot-candle is to be maintained with higher lamps, the candle-power must be increased as the square of the distances. With lamps 10 ft. apart and 10 ft. high we want 52 c.p.; with lamps 40 ft. high we shall want 834 c.p.; with lamps 80 ft. high we shall want 3,350 c.p. to produce the same minimum illumination of $\frac{1}{10}$ foot-candle. 80 ft. high you will say again is rather absurd, but it was used by Siemens in the City twenty-nine years ago. The lamps were put that distance apart to give the best light, namely, twice the square root of twice the height; they were very well arranged, but they spread the illumination over too large an area, and that is one of the important questions to be considered in regard to the height of lamps. You save in lamps and lamp-posts by using high posts; you can calculate a minimum expenditure with a certain number of lamps per mile and at a certain height, but if you use very tall lamps, unless you are lighting a very wide street, illumination is wasted on the buildings. It seems to me not a very difficult matter to light the large streets. We have good examples in London and elsewhere and on the Continent, but the problem of small streets is more difficult, and it is with regard to them that the figures given by Mr. Harrison are so useful. A great deal more skill is required to get good and sufficient illumination in side streets, and the metallic filament lamp no doubt makes this possible where before, with a carbon filament lamp, it was impossible. Mr. Trotter.

Mr. LEON GASTER: I am glad to see that Mr. Harrison, besides presenting useful data regarding the performances of various lamps, has also not forgotten to point out the need for care in selecting the best method of using them. In designing the lighting of a street, it is very desirable to bear in mind its nature, the kind of traffic, and the main purposes for which the thoroughfare is intended. From the earliest times the provision of illumination was connected with the duties of the police in maintaining order and suppressing crime. The recognition of the value of good illumination in this direction is fully shared by the police authorities of to-day and people in all countries. But in modern times, owing to the increase in vehicular traffic, there has arisen a new and somewhat distinct aspect of street lighting. During the last few years especially the nature of London traffic has radically altered, more particularly as regards the speed of motor-driven vehicles. One of the most important functions of street illumination now is to assist the police in the regulation of this traffic, and to enable pedestrians and vehicles to distinguish clearly approaching motor-cars, etc. Now, for this purpose, it must be realised that the production of a certain illumination over the roadway is not all that is wanted. It is also most essential that the lamps themselves should be so placed as not to dazzle and bewilder people by their brilliancy: the dazzling effect of injudiciously placed lights may, in extreme cases, go far to undo all the benefit which their improved illumination should secure. This fact has already been recognised by Mr. Gaster.

Mr. Gaster. the police authorities in the City of London by their recommendation regarding the screening of powerful lamps outside shop windows on the side facing the street. It is clear, therefore, that this second condition—that of facilitating traffic—also tends to make street illumination a matter of consequence to the police. It may also be conjectured that this question will be of interest to the newly created Traffic Board. Now, seeing that this illumination is provided very largely for the benefit of motor traffic, and that it has already been decided that the owners of motor-driven vehicles ought to contribute to the upkeep of the roadway, might it not be also suggested that the cost of providing this extra illumination should be partially defrayed from their contribution? Drivers and owners of motor-cars, I am confident, would welcome any attempt to improve the lighting from their standpoint, and would cheerfully pay something to secure really satisfactory conditions of illumination, not only for the main thoroughfares, but also for side streets which are now quite inadequately lighted.

Having touched upon some of the main purposes of street lighting, I should like to say a word or two regarding the suggested standard lighting specification. It seems now to be generally recognised as desirable that an agreement on the subject of street lighting should contain some specific reference to the illumination provided, and that this should be checked by some form of photometric measurement. There has, however, until recently been great diversity of opinion as to the best method of testing. Different methods have been advocated by representatives of gas and electric lighting, and there has been much discussion as to whether measurements of illumination should be made in a vertical or horizontal plane, etc. It seems to me the time is now ripe for some attempt to secure agreement on some one system, and in this connection I should like to mention the precedent set by the Verband Deutscher Elektrotechniker, in Germany, who have appointed a photometric commission to inquire into this matter.* This commission recommended that measurements should invariably be made in a horizontal plane 1 metre above the ground, and that this same method should be used for general specifications both of interior and outdoor lighting. Moreover, the suggested basis of a specification on these lines has been submitted to the German Institute of Gas Engineers with a view to securing something that will be acceptable to both bodies, and will be adopted for common acceptation throughout Germany. I therefore welcome the suggestion of Mr. Sparks, that a committee should be appointed to discuss this matter, and I think that it might profitably include in the scope of its inquiry some investigation into the general objects of street lighting. I may add that, in order to be successful, this committee should be of a thoroughly representative character, and comprise gas engineers, electrical engineers, surveyors, and representatives of all those intimately concerned with street lighting.

* *Illuminating Engineer*, vol. 3, p. 403, 1910.

I have often pointed out the singularity of the conditions under which every borough adopts the method of lighting that pleases itself, so that London becomes a sort of laboratory for street lighting; independent experiments are being constantly carried out, often leading to results which cannot readily be compared and from which it is difficult to draw any general conclusion. I have therefore advocated for some time past the placing of the street lighting under the control of a central authority, which is to treat this matter in the same way that water supply and sewage disposal are now dealt with. The tendency in this direction has been illustrated by the increased interest recently taken by the Local Government Board in street lighting, but I feel that if this body is going to deal with the matter it should provide itself with a special engineering staff and secure such representative and authoritative expert opinion as to entitle its directions to unqualified support. Mr. Gaster.

In conclusion, therefore, I wish to express my agreement with the suggestion of Mr. Sparks, and I hope that the contemplated committee will be in a position to deal impartially with those fundamental problems of street lighting which are of interest to the gas and electrical engineer alike. I may add that during my recent visit to the Continent I found everywhere the impression prevailing that the objects and principles of street lighting had not yet been sufficiently discussed, and the conviction that a committee on the proper lines might do considerable service. It is now recognised that good street illumination is what we pay for, but as to what this consists in we are not yet in complete accord. I may add that it has been our experience in the Illuminating Engineering Society that such knowledge can only be derived by the co-operation of those concerned with all the different aspects, physiological, architectural, and engineering, involved in these problems, and for this reason we are endeavouring to provide an impartial platform where representatives of all these different standpoints can meet together. Any assistance we can render in this matter, I have no doubt, will gladly be given by this Society.

Mr. W. R. Cooper: I merely wish to call attention to one point to which Mr. Kenelm Edgcumbe referred elsewhere some time ago. If a lamp is fitted with a reflector, or particularly if it is placed in a dioptric globe, the term "candle-power" as usually defined does not apply until the photometer is beyond a certain distance from the source. The reason for this is that the rays no longer emanate from a point, and the inverse square law does not hold. An extreme case of this is the projector, or lighthouse, throwing a parallel beam; such sources have often been spoken of as giving millions of candle-power, which is absurd, because the value obtained will vary according to the distance the observer is away from the source. As to whether there is an appreciable error in measuring, say, the Union lamp with clear dioptric globe in street measurements I do not know, but I think it would be well to decide the point experimentally, as specifications dependent on candle-power measurements are coming into fashion. I should like to know if Mr. Harrison has measured the candle-power in such a case by two Mr. Cooper.

Mr Cooper. photometers at different distances along the same ray as nearly simultaneously as possible, such distances being the shortest and longest limits that would be usually employed, and has obtained practically the same candle-power.

I am sorry that Mr. Harrison has introduced the term "diversity factor." Could not another term be found, considering that this one already has an acknowledged meaning? If not we shall have illuminating engineers striving for a small diversity factor, and supply engineers for a large one, which is rather absurd.

Mr. Shaw. Mr. C. M. SHAW: On page 25 the author mentions that in Marylebone the old lanterns were adapted. In Worcester we have tried almost every type of lantern over a period of 10 or 12 years, and I arrived at the opinion that it was far wiser to scrap every one of them and have no glass protection at all. In these days of motor-cars, when the dust on the roads is excessive, the glass lanterns soon look very dull. With regard to Mr. Vignoles' remark that external glass increases the light, it certainly appears to do so for about a day, but this effect soon dies off. The unnecessary expenditure incurred for cleaning might be used to better advantage in increasing the power of the light. With regard to the price at Marylebone, we have to quote a very much lower price than £3 15s. per post in the provinces to make great progress in beating gas competition. On page 29 the figure of £204 is mentioned as the charge for side-street lighting. I wish we could get that amount in the provinces. I am very satisfied if I get £120. On page 33 the author mentions that the tungsten lamps give a better result at a lower cost than the ordinary open type of arc lamps. I have found that to be correct, and am throwing out every one of our open-type arc lamps as fast as I can. There is another system I have not heard mentioned in the discussion nor in the paper, for lighting streets where no mains exist. In Worcester during the past twelve months we have carried out a scheme, using overhead wires, affixed to the tramway poles, with double-arm brackets on each pole to contain two 35-c.p., two 50-c.p. or two 100-c.p. lamps according to the importance of the street. The standard annual inclusive charge for all candle-powers is £2 18s. 6d., or £117 a mile. The cost of fitting up equipment, including brackets, insulators, three wires to enable half the lights to be extinguished at midnight, time-clock switch, and the first charge of metal lamps works out at £195 per mile, which expenditure is debited to revenue account, thus avoiding the trouble of applying to the Local Government Board for loans. These lamps are fixed 16 ft. from the ground. There is not the slightest glare, and we get almost perfect illumination along on the street surface. I may say that the citizens are extremely pleased with the arrangement and want the system extended.

Communicated: With respect to the remarks made by Mr. Trotter as to placing modern types of arc lamps at greater heights than obtain at the present time, he stated that it might be advisable to fix them even at a height of 80 ft. During my recent visit to America, I noticed

at Detroit that 60 lamp towers were in use, and as far as I can remember, three or four enclosed arcs were fixed in each tower at a height of about 120 ft. from the ground. The area of ground lighted by this method was large; the effect, however, was not as good as that which might be expected from flame lamps, which should give an extremely effective illumination. Mr. Shaw.

Professor Morris.

Professor J. T. MORRIS: This paper is one which is bristling with points that one would like to discuss. As time is short, I propose to confine my remarks entirely to the subject of diminishing the glare from lamps. It is an open question whether when one looks along a well-lighted street, the actual sources of light should or should not be visible. I think that most people who have to pay for the lighting of the streets would say that they should be visible, and that it gives a more decorative effect. On the other hand, I believe that if the street lighting is done not for decorative effect, but with the object of enabling pedestrians and drivers of vehicles to see clearly, then it is unwise to have the sources of light visible when one looks along the street horizontally. Therefore I submit that if what we want to do is to light the streets well without regard to decorative effect, the lamps, at any rate, ought to be screened down to between 10° to 15° below the horizontal. If we are lighting the outskirts of a village, where lamps are used, as Mr. Sweet calls it, as "street markers," and placed so that one just loses the light from one lamp before catching the light from the next one, then they undoubtedly should be visible. Passing to the subject of the best way of diminishing the glare from lamps, I have often had occasion to notice in the streets of Marylebone the diminution of glare resulting from the use of two bright white curved surfaces above the lamp. In order to test this matter, and to try to get at the reason why this does diminish the glare, I made two or three experiments on the measurement of the size of the pupil of the eye when inspecting a lamp under three conditions: First of all looking straight at a tungsten lamp with a clear bulb at a distance of 10 ft.; next, putting a mirror behind it so that the reflection of the lamp in the mirror as well as the lamp itself is seen; and, thirdly, removing the mirror and putting a sheet of white paper behind the lamp. The two people who were experimented on both said that when the white paper was behind the lamp it was undoubtedly more restful to look at than in the other two cases, although the addition of the white paper considerably increased the light falling on the observer. The mean of a number of measurements of the area of the pupil of the eye of the two observers gave the following results: With the naked light the area of the pupil was taken as 100 per cent. When the mirror was placed behind, then the pupil contracted to 85 per cent., *i.e.*, 15 per cent. of the area was cut off, but when the white paper was put behind, instead of contracting, the pupil expanded, so that the area increased to 110 per cent. The remarkable fact brought out by these experiments is that though the illumination received at the eye is about the same in the two cases of the mirror and the white paper respectively,

Professor Morris.

yet the pupil of the eye is larger by 25 per cent. when the white paper is used; therefore the latter form of illumination is more useful, and, at the same time, more restful. To sum up, it would appear that sudden changes in illumination are not only bad in time but also in space.

Mr. Russell.

Mr. C. NEWTON RUSSELL: I think this will prove to be one of the most useful papers to Borough engineers that we have had at this Institution for a long time. I do not propose to take much of your time this evening, as I have not had the opportunity of going through the paper as carefully as I should have liked. So far as working at Shoreditch is concerned, where we have 50 miles of streets, 8 of which are illuminated by the open type of arc lamps, the remainder have hitherto been lighted by gas lamps with incandescent mantles. We carried out some experiments about a year ago to see if we could do something in the same direction as Marylebone, and after thoroughly demonstrating the matter to my Committee, they were impressed with the figures put before them, and we have now started to clear the gas out altogether. We have changed between 300 and 400 lamps, replacing the gas mantles by 50-c.p. and 100-c.p, metallic filament lamps. We find that we get a better light and save the Council money, and also do some good to the generating station. We are accumulating a certain amount of data with regard to the useful life of these lamps, and other matters which are of very great practical value. The average life of the metallic filament lamps in this district is at present 950 hours. This is rather a shorter life than is obtained in other parts, and may be accounted for by the heavy traffic in this district.

Mr. Edgcumbe.

Mr. KENELM EDGCUMBE: Most of the points I had intended to raise have been already much better dealt with by other speakers. I should like, therefore, only to emphasise the importance that I feel attaches to the drawing up of a satisfactory specification for street lighting. Mr. Sparks has proposed that the Institution should appoint a Committee to consider the question, and I was actually going to make the same proposal. I can only hope that the Council will see their way to carrying out the suggestion. It seems to me that they would in that way be assisting the lighting industry almost more than in any other. The only point I am a little doubtful about is as to whether it would be altogether politic for this Institution to do it by themselves without inviting representatives from the gas industry, and possibly from among the surveyors as well, to co-operate with them.

Mr. Boot.

Mr. H. L. P. BOOT: I have read through the paper with great interest. Fourteen years ago Tunbridge Wells was one of the pioneers in street lighting, and then used a formula which I have looked for in vain in this paper, namely, "one arc lamp equals one policeman." There is one point mentioned in the paper to which I would like attention given, and that is the question of side-street lighting by hanging the lamps in the centre. I cannot help thinking that in side streets, which are always very narrow, it would be possible to design some sort of an arrangement by which the light was hung in the centre instead of close up against a building. No doubt the author, with his ingenuity,

will bring out some fittings suitable for this purpose. Another point he mentions—and I think this is a point which settles whether we are going to have street electric lighting or not, because the gas companies are going ahead very quickly—is the question of the cost of electrical energy. It has always appeared to me, where I have gone through estimates, especially those estimates which have been severely criticised by a certain Local Government Board inspector, that the price put down for the cost of electrical energy is certainly too high. Central station engineers will bear me out when I say that having got the plant and everything running, to add a very slight additional load, and a load which gives very nearly 40 per cent. load factor, the cost of generating that energy is infinitesimal. Instead of coming out considerably over 1½d.—a price which I have often heard stated—from actual tests I have made, where I have allocated boilers and everything else specially to the purpose, the price comes out at very little over ½d. per unit, and that is not in large, but in small towns. One of the great reasons at the present day which prevent the adoption of street lighting is the cost of the metallic filament lamp. I do ask the lamp-makers, if they are anxious to see public street lighting throughout the country, to consider some method by which they can produce a metallic filament lamp at a reasonable price, because as soon as the price comes down within reason, there is no doubt at all that electric street lighting should be adopted as the most economical lighting for all side streets. A short time ago we were in trouble in a little city which I am advising, because we were given the option of taking over the lighting contract on condition that we were prepared to light the entire city. This naturally meant a very heavy expenditure on cables. But fortunately the Board were wise enough to face that expenditure, with the result that they have secured a contract for five years for lighting every single gas lamp or other public light in the city. Before the mains were finished we had this additional advantage, that consumers have been coming on all along the routes, so that it will already, without any public lighting, more than amply repay us for our progressive action. Mr. Boot.

Mr. J. S. Dow: It is satisfactory to observe that Mr. Harrison lays stress on the fact that uniform distribution of illumination alone does not constitute effective street lighting. The effect on the eye of the sources of light used is possibly as important a matter as is the uniformity of illumination on the pavement, and it seems likely that in future discussions, even more importance will be attached to the effects of "glare" than at present. It seems that in lighting a street it is almost always necessary to effect a compromise between these two things. The very rays which are essential to the production of good illumination at the parts of the pavement most remote from the lamp are also those which are apt to be most troublesome to the pedestrian, since they fall in line with his normal direction of vision; prismatic globes intended to secure uniform illumination by spreading out the light sideways should therefore also be carefully designed to avoid Mr. Dow.

Mr. Dow. glare. In the paper by Mr. Sweet to which Mr. Harrison refers an attempt is made to show how these two conditions can be reconciled. It is suggested that the ratio between the distance apart of two lamps and the height of the source above the pavement should not exceed 4 : 1. It is also pointed out that rays which strike the eye at comparatively oblique angles produce a relatively slight impression of glare; Mr. Sweet therefore advocates that the direct rays from the source should not strike the eye at angles with the vertical of more than 60°. Curiously enough, this is in exact accordance with the recommendation of Professor L. Weber, of Kiel (made, I believe, quite independently) regarding interior lighting. Nevertheless, this is again merely a compromise, and it is conceivable that in the future it will be recognised to be well worth while to sacrifice a fair amount of light in order to tone down the intrinsic brilliancy of sources and to secure the gain in effectiveness following complete absence of dazzle.

There is another possible method of reducing the tendency to glare, and so producing external conditions of illumination more closely resembling those in interiors. The dazzling effect of street lamps is largely a matter of contrast; the lamps themselves do not appear nearly such brilliant objects when seen burning in the daytime, chiefly because the brightness of the surroundings is so much higher. People who have not made actual measurements would hardly credit the brilliancy of even darkly tinted surfaces during the daytime. By means of this little instrument (exhibited) I have been making some measurements of the brightness of various surfaces in the streets of London. I have also measured the brightness of the illuminated frieze which supplies the light to this lecture theatre—at the centre it is about 5 candle-ft. Yet, as a matter of fact, the sooty exteriors of buildings, monuments such as Nelson's Column, dark trunks of trees, etc., are, under average daylight conditions, often far brighter than this, although they strike us as relatively dark objects. However, most of these surfaces reflect so little light that it is difficult to make a street appear really well illuminated at night however much light is lavished upon it. Occasionally in the case of new buildings which are light in tint we do encounter surfaces which reflect a moderate amount of light, and the improvement in the appearance of the street is immediately apparent. I have found surfaces of this nature having a brightness as high as 1 candle-ft.; when it is recalled that the brightness of the frieze in this theatre is only 5 to 10 candle-ft. (about), it can readily be seen that a large building having this degree of brightness is not to be despised as a means of illumination. It may be suggested, therefore, that street lighting would be given a much better chance if some means were found of increasing the number of light surfaces and so producing a moderate general illumination. The same effect would be aided by encouraging private local illumination by mildly illuminated signs and advertisements, and by the effective illumination of the exteriors of attractive public buildings, etc. If the many places of entertainment which at present merely suspend flame arc lamps

immediately above the pavement could be induced to use this light in the more reasonable form of an illuminated inscription or frieze, both they and the public would probably benefit. It may be suggested, in short, that it is worth while to pay a little more attention to the nature of the surfaces illuminated and not to concentrate attention only on the sources of light and their arrangement. Professor Weber has suggested that in order to avoid dazzle we should endeavour to tone down the brightness of surfaces so that the ratio of their intrinsic brilliancy to that of the illuminated surroundings does not exceed 100:1. In the same way a certain minimum contrast seems necessary, for it is naturally difficult to render objects distinguishable from each other which have approximately the same colour and the same reflecting power. For example, whitening the edge of a railway platform, and thus increasing its contrast with the rail-bed, may be a vastly more effective means of showing passengers where the platform ends than doubling the illumination would be. Mr. Dow.

In conclusion, I should like to echo Mr. Gaster's expression of satisfaction with the suggestion that a committee should be appointed to deal with street lighting and its problems on impartial lines. The Illuminating Engineering Society has laid stress on the fact that there are many problems of this nature which are of common interest to all those concerned with street lighting, and I feel sure that this Society and their hon. secretary would be only too glad to give support to the proposal and assist in securing a committee of the desired representative nature.

Mr. S. E. FEDDEN (*communicated*): With regard to the position of the posts as referred to on page 24, my experience is that the determining factor in choosing the position of the posts is not so much one of least disturbance to individuals as the necessity of meeting police requirements. Referring to the retention of the existing lanterns, as mentioned on page 25, the size of the lanterns must be taken into consideration on account of the labour necessary for their cleaning; this, in the case of the conversion of a 3- or 4-light burner being considerable. On page 26 mention is made that the capital expenditure worked out at less than £3 per post. I should like to have particulars as to the class of cable used, reinstatement charges, and also whether switches or fuses were included in the fittings. As regards the details of the tender of the electricity department mentioned lower down on page 26, it would prove interesting if the author could give corresponding figures for gas, so as to show where the principal saving was effected. In the absence of these figures I have calculated the number of units consumed per hour as 1,870. This gives the lighting hours as approximately 3,570 per annum, which gives no margin for operation by hand. Were automatic switches used, and was the saving principally effected by the reduction of the burning hours? Also, what was the price of gas? Turning to the second table on page 27, I should like to know how much the charges for B and C have been reduced. Mr. Fedden.

Mr. Mackenzie. Mr. JOHN D. MACKENZIE (*communicated*): In the table on page 28, giving the candle-power of the gas mantles in the original posts as compared with the candle-power of the tungsten lamps now installed, can the author inform me at what angle the candle-power given—viz., 45 c.p. and 76 c.p.—was obtained? I presume that the 20° and 10° mentioned are from the horizontal. I should also like to know how dirt affects the illumination given by the Marylebone reflectors, and how much attention is required to keep these reflectors clean. Can the author give us any information as to the comparative cost of (1) upkeep of gas mantles as compared with tungsten lamp renewals, and (2) cleaning and repairs of gas mantles as against electric tungsten lamps? I am interested in the author's conclusion that small lighting units placed at moderate heights and spacing give a more uniform illumination. Personally, I think that a great deal of harm is done by the use of high candle-power units placed large distances apart; the disproportion between maximum and minimum illumination is so apparent, and gives such a very patchy appearance to the street lighting. The only objection I see to the use of small light sources is that such very intense illuminating sources are used in shop-front lighting, and unless a certain proportion exists between the candle-power of the private and public lighting units, the former may completely dwarf the latter. Speaking of arc lamps for use outside shop-fronts, I am pleased that the increased use of flame lamps with the larger globe, and consequently softer lighting effect, has to a great extent displaced the single enclosed arc lamp with its very small and intensely brilliant opalescent globe. I think there was nothing more trying to the eyesight than this light source.

Mr. Sexton. Mr. F. PEAKE SEXTON (*communicated*): I should like to point out the importance of the practical determination of candle-power—in contradistinction to its theoretical calculation—in all systems of illumination both exterior and interior. It is ten years since I first considered this question, at which time I had the pleasure of working with Mr. Harrison, and although my experience is not as extended as that of several of the members of this Institution, I think that I can realise the good work that Mr. Harrison and others are doing by their untiring use of the photometer. Photometry rests on the fundamental inverse square law—a fairly exact principle, if applied to an isolated light devoid of globes, but when an attempt is made to apply this simple law to the complication of a dioptric arc or Holophane reflector, the principle naturally fails, and the pure calculator is led into hopeless errors. In modern illumination I might say it is almost always impossible to calculate the candle-power at a distance even if the local effects of surfaces near the photometer are eliminated. Although this point is becoming more clearly recognised, I noticed that it was not fully appreciated during the discussion following the reading of this paper. I would urge the Council to propose a standard specification for street lighting, as there is no doubt, to my mind, that the electrician is more often an expert in illumination than the gas engineer. The

proposal that several speakers raised with reference to the fixing of a ratio between rays at different angles is hardly sufficient, unless the distance from the source is specified in both cases; but I need not labour this point after what I have said above. In conclusion, I press the point that all calculations should be only accessories to the photometer, and certainly not independent of its use. Mr. Sexton.

Mr. H. D. WILKINSON (*communicated*): The author has placed at the disposal of members in this very welcome and able paper first-hand information of the costs of gas and electricity in street lighting which will be of considerable assistance to those who have street-lighting problems before them. With reference to the effect of height of lamps on horizontal illumination dealt with on page 42, I think a point not touched upon in the discussion is the fact that if the minimum horizontal illumination is increased by placing lamps higher without increase of candle-power, the illumination from the vertical rays is reduced. The cosine factor ceases to be dominant inside a radius of about 20 ft. from the lamp at heights exceeding 10 ft.—that is to say, as the height is increased the illumination falls off in the inverse square of the lamp distance to a greater extent than it gains by the cosine factor. For the same reason the gain of 50 per cent. minimum horizontal illumination in the Baker Street lamps by raising them 8 ft., as suggested in the paper, would be counteracted by a loss of horizontal illumination inside a radius of about 25 ft. from the posts. Taking account of the characteristic A in Curve VI., it would appear that this loss would amount to 40 per cent. at about 15 ft. radius, which would be a distinct disadvantage, particularly at corner posts where the lighting of the roadway depends upon the maximum illumination. Posts are usually set near the corners of side streets to give this special lighting, and the object would not be attained if the maximum illumination was sacrificed to obtain uniformity. This explains and supports the author's suggestion in the paper, that a perfectly uniform horizontal illumination is not ideal, and does not correctly meet the conditions in practice. On the other hand, with flame arcs the illumination ratio is so high that every means must be taken to raise the minimum to a satisfactory amount. In the tests on flame arcs in Cannon Street and Holborn carried out 2½ years ago by Mr. A. A. Voysey, the electrical engineer to the City Corporation, 0·1 candle-ft. was found to be the minimum illumination for satisfactory lighting of busy main streets, and this is now considerably exceeded in the Cheapside lighting alluded to by Mr. Frank Bailey. The scheme for the City recommended by Mr. Voysey, on which he estimated at that time a saving of £6,000 per annum over gas with double the illumination, appears to be well in progress, and considered with the more recent lighting by tungsten lamps in Marylebone and Croydon effected so successfully under the author's guidance, there should soon result a desire amongst other municipalities to make a similar advance. Mr. Wilkinson

On the subject of height and spacing Curve V. is very instructive, but would appear to be based on an impracticably high candle-power

Mr. Wilkinson.

at the lamps. Taking into account the combination of rays from two consecutive lamps at the position midway between them, as in the figures given in Table VI., the 2-candle-ft. illumination in the top curve for 40 yards spacing would appear to require lamps giving 10,000 c.p. It would render these curves more useful if they were modified for lamps of 2,000 or 4,000 c.p. within the limit of 27° from the horizontal dealt with. For instance, lamps spaced 40 yards and fixed at 30 ft. height would give a minimum horizontal illumination of 0·4 candle-ft. if the rays at this angle were taken at the more practical figure of 2,000 c.p. On the question of flame-lamp globes I recently took a set of observations, using the author's photometer with inclined flicker disc, on a 10-ampere alternating-current Beck flame lamp with opalescent globe, suspended at heights up to 27 ft. in the open. The rays at horizontal angles under 30° came out less, and those above 30° higher in candle-power than shown in profile C of Curve III., and the mean hemispherical candle-power also was less. Perhaps the author would tell us whether the observations in the curve were on direct-current or alternating-current lamps, and if the latter, whether the difference in profile could be accounted for by a different degree of opalescence in the globe.

Mr. Scott.

Mr. E. Kilburn Scott (*communicated*): Posts in the centre of a street, especially where there are tramways, are exceedingly dangerous owing to the possibility of passengers jumping from the off-side of the cars. Great George Street, Sydney, used to be lighted in this way, but all the posts have now been removed as being too dangerous. When there are buildings along the streets to which brackets can be directly attached, what is the use of having either posts or span wires? The latter are nearly as objectionable as posts because of their interference with the free movement of fire escapes, and the ragged appearance of the hanging cable that carries current to the arc lamps. In my opinion brackets attached to the buildings, having arcs for the widest streets and metal filament lamps for the medium and narrow streets, would make the best job. It would be no hardship to the owners and occupiers of buildings, because rosettes are now fixed on the walls or else posts are placed close up to the buildings. Further, I propose that behind each lamp there should be a white reflector, or else the wall of the building be painted a light colour. In this way the light would be thrown forward into the street. On this reflector there should be the name of the street, the number of the building to which the bracket is attached, and also, if sufficiently important, the name of the building. Strangers would thus be able to find their way about at night just as easily as by day, which is not the case at present. I take more than ordinary interest in the question of street lighting of London because I am one of the many victims of the present bad lighting combined with high-speed taxi-cab driving. In the Strand, Holborn, Queen Victoria Street, and Embankment there has been some little improvement, but the lighting in what may be called the main east and west arteries of London is still far from what it should

be. This is especially noticeable round about the island churches of the Strand. Mr. Scott.

An interesting development in the improvement of street lighting is now taking place in Bromley, Kent. Both the gas and the electricity supply are in the hands of companies, and the municipality has a contract with the gas company for lighting the streets. The tradespeople in the High Street have been dissatisfied for some time, and they have at last taken the matter into their own hands and arranged a contract with the electric light company for arc lamps. A committee of tradespeople is managing the whole business. They have obtained permission for rosettes to be fixed to the buildings, and are allocating the initial and the running expense to the various shopkeepers who are benefited by the improvement.

Not to be beaten, the gas company has come to a somewhat similar arrangement with the shopkeepers in the Broadway, Bromley, and high-pressure gas lamps are to be installed. It may be of some interest to mention that the lighting of main shopping streets in warm climates is somewhat difficult because of the very wide permanent verandahs that come right down to the kerb. There is much promenading in the evening under such verandahs, and the lights have therefore to be underneath. In Melbourne arcs are used, and the effect is very brilliant, almost blinding; the arcs are necessarily low down. Everything points to the need for some tube system being brought out to meet this special case. A line of light along the edge of the verandah, which would light the causeway as well as part of the roadway, should be very effective.

Mr. E. P. Hollis (*communicated*): Despite the long discussion to which the subject of street lighting has of late been subjected, no one in this country appears yet to have attempted to reason out the basis on which a street-lighting specification should be prepared. That we should establish some definite basis is apparent, for in future the majority of street-lighting contracts will be let on tenders to a photometric test. It is not always that the task of preparing a specification falls to the expert illuminating engineer. In the future it will often fall on some non-technical person, such as the borough surveyor. Holborn is a case in point. If such a person were at this moment called upon to perform this duty he would look round in vain for material to assist him. So far as I am aware, only one specification on a photometric basis—that for Westminster—has been put into force in this country. In considering this question it is well to remember that there is a class of persons who openly scoff at the idea of subjecting street lighting to a photometric test at all. They base their opinions on facts that cannot be refuted. They point out that in many instances lamps are situated in positions dictated by other than photometric considerations: lamps are put at street corners, in already existing gas lamps and various irregular positions, so that all attempts to obtain accurate illuminating effects are a waste of time. Mr. Hollis.

The question I propose to discuss is: On what should a street-

Mr. Hollis. lighting specification be based—on candle-power, on illumination, or on surface brightness? It will be convenient to take surface brightness first. Surface brightness is what we want, and, if it were possible, surface brightness would constitute the ideal basis. Unfortunately there are many things which militate against it. It is extremely variable, according to the object on which the illumination falls and according to the condition of the weather. The difference between the brightness of a white object and of a dark object subjected to the same illumination is so enormous as to preclude any attempt to adopt surface brightness as the basis. Besides, what an enormous divergence there is in the views held as to the object on which the test should be taken! Some people demand illumination sufficiently good to pick up a pin; in that case it is the brightness of the road that matters. Others want to read a newspaper or look at a watch, but the illumination which would suffice to do either of these two things might not satisfy the man who wanted to pick up a pin. And there are many other views; but whilst surface brightness is the test for many indoor lighting purposes, in a street lighting specification it is impossible. That brings me to the question of illumination.

Illumination is, as it were, the raw material from which surface brightness is produced, and is the only criterion, excepting surface brightness—which I have just rejected—by which we can judge whether a street or an object is suitably lighted. It would be possible for any one to specify the minimum and maximum illumination for a street, and leave everything to the suppliers of the energy. It is left for them to instal what units they liked, to space them how they liked, to employ whatever reflectors they see fit, and to place the units at any height they pleased. That means that plenty of room is left for enterprise. Some one might propose to sling small units centrally across the street. Why should they not? But they could not do it if a high candle-power unit were specified. There is, however, one great drawback to illumination as a basis. Whatever that basis may be, it must be possible to go to the contractor and say, "Your light was low last night. You must pay the prescribed penalty." That, of course, is the whole object of the specification. But if the contractor can reject the tests on the ground that their accuracy was open to question, then that basis is quite useless. As things stand at present, illumination cannot be measured sufficiently accurately and with reliability by a casual test working with ordinary apparatus under street conditions. On an illumination basis the contractor could justifiably reject unfavourable illumination tests unless he had been personally present, and was satisfied that the accuracy of the testing apparatus was above suspicion. On this ground illumination must be rejected as an ideal basis.

Coming to the remaining basis of candle-power, it will be remembered that the Westminster contract was based, or was supposed to be based, on candle-power. It was prepared on the assumption, now known to be without foundation, that the candle-powers measured at angles of 20° and 50° to the horizontal afforded some

Mr Hollis.

criterion of the mean hemispherical candle-power. Now, even if they did, the mean hemispherical candle-power of a unit does not give us the slightest idea of how that unit would distribute its light along the street, so that on that basis alone candle-power must be unhesitatingly rejected as being far inferior to illumination. Again, to specify candle-power involves the draughtsman of the specification in a large amount of consulting work. He has to decide upon a surface brightness, then upon the illumination to produce it, following which he has to juggle with the height of the lamps, their distance apart, and the angle of their maximum candle-power before he can finally decide upon what mean hemispherical candle-power he thinks he would like. Even then he hardly knows what he is getting.

Supposing that mean hemispherical candle-power be specified, there is no practical method of measuring it in the street and no suggestion of a method has ever stood criticism. It would seem, then, that candle-power as a basis is hopeless. It has, however, one redeeming feature; the candle-power of a lamp at a particular angle can be measured with extreme accuracy, and this fact provides us with what is, in my opinion, the only basis on which a specification can be prepared. I suggest that a minimum horizontal illumination be specified, and, on a suitable night, when the test is to be taken on which the acceptance or rejection of the installation depends, the position and value of the minimum horizontal illumination between two lamps be accurately determined. It would be possible under such conditions to measure the illumination with great accuracy if a suitable illuminometer were used. Having determined the value of that minimum illumination and its position, turn a photometer on to each of the two lamps and measure their candle-power and the angle to the lamps on either side of the spot. Having once determined those two quantities—the angle to the lamp and the candle-power at that angle—it would be possible to come back every night and by taking two simple candle-power readings, *i.e.*, by measuring the candle-power of each lamp at its particular angle from the same position, to determine with the greatest accuracy in a few seconds whether the illumination was up to specification; for the candle-powers at these angles would provide a continuous criterion of the performance of the lamp. It is only on such a basis, in my opinion, that a satisfactory specification could be based. Of course, should the illumination found on the test-night exceed that specified, then a suitable reduction in the candle-power demanded would be made.

At the present stage of the development of lamps and reflectors it would be rather difficult to specify a diversity factor, for although in theory we can calculate from the polar curve of a good lamp a diversity factor of 3 or 4, in practice the reflection from the walls and buildings in the vicinity of the lamp greatly increases the illumination in those parts.

Discussion before the Manchester Local Section.

(*November* 22, 1910.)

Mr. Pearce.

Mr. S. L. Pearce: By way of criticism there is very little that I wish to say, as I almost entirely agree with the whole of the subject matter before us. There are one or two points, however, that I would like a further explanation upon by the author of the paper. On the bottom of page 24, Mr. Harrison quotes a statement made by Dr. Louis Bell before the Illuminating Society of America, namely: "Street lighting has been a growth and an evolution, but like all growths it has proceeded to a certain extent along the lines of least resistance; lamps were put, not in the best places for them, but where they could be put in with the least disturbance to individuals." I simply wish to endorse that, and fully agree with it. As is so often the case, engineers are not always allowed to choose the best positions for their lamps. For instance, lamps have to be placed at street corners to allow for illumination down the side streets. In that case the illumination of the main thoroughfares becomes somewhat uneven if the lamps are of uniform candle-power. On the middle of page 25 Mr. Harrison describes the method of having two Osram lamps in series in the lanterns. The advisability of having two lamps in series is, I think, a little doubtful, because if one goes, there is then no light. They took special precautions at Marylebone by adopting the anti-vibration suspension. I think they could just as well have used the ordinary 230-volt lamps in parallel. I believe that is done at Eccles, but as Mr. Angus is present, perhaps he will explain. I am sure that all who have seen the Marylebone lighting will agree that it has a most excellent effect, and the author is to be congratulated for his share in securing that desirable end. On page 26 I am not quite clear as to Marylebone's treatment of these charges. Mention is made that in one district no existing distributors were available, and therefore new ducts and mains had to be laid. I presume there he refers to new distributing mains. He states a few lines further down, "£1,640 would still be available for electric supply if the existing gas rate were still charged for lighting." I do not quite see why it should be. Mr. Harrison states that the allocation of capital charges on mains is a very difficult matter. I do not see why. It is easy to ascertain what the relative demand is on the mains. I suggest that the amounts on public and private lighting be allocated in accordance with the respective demands on the main.

There is one line on page 27 which I must confess I do not like at all, namely: "This figure was not arrived at with any idea of the cost to the electricity department." I rather suggest that that is the kind of matter the editor of the *Gas Journal* would like to get hold of. On page 38 a method is indicated for arriving at street-lighting costs. The allocation as between standing and running charges is quite simple to do, and I suggest that there should be no difficulty in arriving at what the true cost is. From the author's paper it reads as if the

Marylebone authorities had settled in their minds on a lump sum for the whole contract. Items of capital charges on services and on the electric-light fittings are deducted, and that gives you a certain balance which represents the inclusive cost per unit. I venture to suggest that is putting the cart before the horse, and I can hardly suppose this to be an actual statement of fact. In the middle paragraph on page 27 it states: "£1,170 per annum for repayment of cost of services, etc., the cost of the repayment of the electric fittings being already allowed for; this will easily wipe off the cost of the services in five years; therefore if a 10- or 15-year loan had been arranged the price per unit could have been reduced to 1d. per unit." I do not see there any reference to capital charges on the distributors. It is capable of more explanation. On the bottom of page 29 there is a very important paragraph stating that arc lamp makers are improving their lamps. There is no doubt that any one testing modern flame lamps knows that the distribution is very unsatisfactory: there is a brilliant glare at the base of the post, and a very rapid diminution of illumination as the distance from the post increases; and I hope that the lamp makers will turn their attention to this most important point, with a view to the design of a correct globe, and that clients will not be willing to take anything sent to them. Mr Pearce.

With regard to the height, they recommend 30 ft., but this is rarely possible of attainment. There is no doubt that the adoption of the inner dioptric globe is a great advance, and I think there are at least three benefits to be gained. There is the increase in candle-power as shown in the middle of page 30 by the author, but there are two advantages also which are not pointed out in the paper. The first is that more efficient ventilation can be secured, and by that means we avoid a good deal of the silting-up of the bottom of the globe, and we avoid carbon deposit, and so eliminate the cutting off of a very large percentage of the light. The second point is that by the adoption of this inner globe we are able to prevent the etching of the outer globe which goes on during hours of burning owing to the action of the chlorine gas. We have found in Manchester that after using a certain type of lamp for about twelve months, something like 20 per cent. of the light is lost through this etching of the globe. The figures which Mr. Harrison gives and the results of the test made by Mr. Morris on page 32 are exceedingly interesting in high-pressure gas lamps. I take it this 1,500-c.p. Keith lamp is the same lamp as a number of those which the gas authorities in Manchester erected in Piccadilly, the figure for which they gave in the papers some time ago. We have had a photometer out on these lamps, and the result of our test on the lamps at Piccadilly was that they had shown a maximum candle-power of about 1,260 at 30°; I am not in a position to put any definite figures before you. I should rather imagine from the above figure for candle-power that they have not been able to maintain the water pressure which I believe was equivalent to 80 in. Probably they found the high pressure had a destructive action on the mantles, and

Mr. Pearce. due to the reduction of the water pressure the candle-power has evidently fallen off to some extent. I think there is also good ground for believing that the consumption is in excess of the makers' guarantee, viz., 25 cub. ft. per hour, and Mr. Morris's figures of 30 to 34 are probably within the mark. There seems to be some shrinkage going on with the high-pressure gas mantles, at times amounting to at least 1 in. I would like to ask Mr. Harrison whether the shorter mantles are likely to give the same candle-power as the longer ones. Apart from fair wear and tear affecting the life of the mantle, there is the most important point of external damage, caused by vibration and so forth, which very seriously shortens the economical life of the mantle and diminishes its light-giving properties.

I rather gather on page 33 that Mr. Harrison comes to the conclusion that there are really only two types of lamps nowadays available for modern street lighting, viz., flame arcs or tungsten groups. There is no reference to the single enclosed lamps, and perhaps this is a little extraordinary in view of Mr. Harrison's remarks in his 1905 paper. He referred to some lighting in the Gorton district outside Manchester, and now within the city. I fully endorse the author's opinion as to the value of street lighting—if we can get it—as a demand having a high load factor, but I do not go so far as to say it is superior to a motor load. It may be of interest to mention that the price we are getting in Manchester is an inclusive price of 1½d. per unit, including capital charges, maintenance, as well as for current.

On the top of page 42 the author makes a remarkable statement with regard to converging flame lamps, and states that, "erected at 70 yards they give illumination at the same cost equal to small units placed between 40 and 50 yards apart." On page 44 the author gives us some interesting information with regard to the "diversity factor," which is rather a strange application of this term. I think the expression of "the ratio of maximum to minimum illumination" given lower down in the paper is better. Also on page 45 there is another interesting result with regard to the high-pressure gas lighting, the rays which reach the point of minimum illumination being only 1·5 times the power of those adjacent to the post. This is a much lower value than would have been expected, and is probably accounted for by the action of the reflectors.

Referring to the curves on pages 31, 36, 43, and 45, the author points out that these are the curves which are issued by the manufacturers, and I venture to suggest that they are substantially higher than those which are obtained in actual practice. In Curve IV. the polar curve given for the tungsten lamp is both remarkable and quite ideal. The curves on page 43 show the horizontal illuminations from two different sources of light with varying heights and varying distances apart, while, if I remember rightly, Mr. Harrison in his paper of 1905 very strongly advocated measurement on a surface inclined at 45° to the horizontal. I should like to ask on what basis all the remaining Curves and Figs. in the paper have been calculated.

Mr. J. FRITH: There is one point in the paper that has not been mentioned, and that is as to how the various types of lamps are affected by fog. As it is in cases of fog that street illumination is far the most urgently needed, any information on the point would be valuable. I am sorry the author has not more fully justified his practice of measuring only the horizontal illumination. Take, for example, the illumination by motor-car head-lights carried very near the ground. Although their illumination is particularly effective for purposes of using the street, they, of course, give next to no horizontal illumination of the street. Mention is made of the illumination up the sides of the buildings. This may not be of much use with the black buildings in Manchester, but in other, more favoured places it might possibly have some effect. Mr. Frith.

Mr. H. W. ANGUS: With reference to the street lighting in Eccles, we have about 300 posts each fitted with a 55-watt 100-volt tungsten lamp in a well-glass fitting, with inverted reflector, mounted upon a swan-neck bracket. The approximate cost of the post, fitting, and lamp, erected, is £2 12s., and the approximate cost of the service including the tee-joint is £1 5s. 6d. I cannot give any particulars regarding candle-powers obtained at various angles, but can only say that the general public are satisfied with the lighting result when compared with the incandescent gas lamps which they have replaced. The cost of lighting main thoroughfares and side streets given on page 29 appears to me to be much higher than small towns such as Eccles could afford. In Eccles the number of posts per mile in side streets is 40 against 65 mentioned in the paper, and in Eccles the cost per mile is approximately £100 per annum. We get a price of £2 8s. 6d. per post per annum, which includes the electrical energy supplied, lamp renewals, and attendance. This sum was based on the cost of energy at 1·92d. per B.T.U., but it also provides for four lamp renewals, the average life of a lamp being assumed at 1,000 hours. Actual results obtained have shown that the average life of these tungsten lamps is over 2,000 hours. The approximate number of hours the lamps burn per annum is 3,800. The lamp renewals per annum have therefore worked out at a little over 1¼ lamps per post. We could, therefore, afford to make a reduction in the price of £2 8s. 6d. [Mr. HARRISON: Does that cover capital charges?] The capital charges do not enter into the question, because the District Fund pay for the cost of the services, fittings, and posts. Mr. Angus.

Mr. A. G. COOPER: I do not think I can add very much with regard to street lighting. I get such a good price that I am not seeking it. We have only half a dozen arc lamps for which we get no revenue at all, as the gas department give the public lighting, and we have to follow suit. With regard to single enclosed arc lamps, I do not know whether any one here to-night has tried putting them on tramway poles. At Colne we are very high up (600 ft. above sea-level), and to this I attribute the difficulty in making the carbons burn anything like the stated hours which enclosed arc lamps are expected to give. It is stated that one can get about 70 to 80 hours for single enclosed twin- Mr. Cooper.

Mr. Cooper. carbon lamps. I have found the life only 50 hours. I am experimenting at the present time, and have already improved the life of the carbons by closing up a small duct which supplies the air to the globe, as they are apparently sufficiently exposed. Whether we shall get bad results on the globes due to deposit I have yet to learn.

Mr. Moon. Mr. O. MOON: The great thing with regard to street lighting is not the main streets to a great extent, but the side streets, and the author has proved by his figures that we can easily compete with gas in the side street with very little outlay with tungsten lamps. About two and a half years ago I was at a debate where it was stated that the tungsten lamps were not able to stand vibration or anything else, and I said that we had no authority to say how long they would last. We had no proof then that the tungsten lamps would last to the extent that they do at the present time. From statistics taken out from fifty towns, it has been shown that we are now getting an average of over 2,000 burning hours. I should like to know what our gas friends have got to say with regard to that. It clearly shows that we can give small units of lights in small streets at very small cost. I think that the only way to get the side streets lighted is by small units of tungsten lamps, which are very satisfactory.

Mr. Sells. Mr. F. SELLS: Mr. Harrison's paper must have been compiled with much trouble, and it furnishes most excellent data for reference. Without wishing to appear ungrateful, I should like to say that Mr. Harrison has just stopped short in one respect, and I deplore that he has not gone one step further in giving us his extensive experience, especially in view of the fact that he has consented to read this paper in Manchester. I do not wish to minimise the value to all of us of the figures and tests obtained in London districts, such as Marylebone, Baker Street, and Victoria Street, most particularly from a general educational point of view and for reference, but after all, how many of us in this district deal with street-lighting figures such as £8,000, or even £5,700? If we have named "Greater Manchester," Liverpool, Sheffield, and Leeds, there are no places left where any expenditure on any scale whatever can be sanctioned, and it would therefore be most interesting if Mr. Harrison could give us his experience regarding street lighting on a small and inexpensive scale. There ought to be a number of station engineers here to-night who have started lighting their streets, and it would be interesting to have some information how they arrange to get the supply, especially in the side streets. Mr. Harrison has dealt in his paper chiefly with street lighting, which has been done recently by way of converting arc-lamp lighting into tungsten, but it would be interesting to have the figures of the lighting of side streets by electricity which had previously been lighted by gas. As we have seen, it is difficult to discuss a paper such as Mr. Harrison has given us, and I have been thinking whether it would not have been a good idea to invite a gas engineer to open to-night's discussion. We, who have listened to the paper, are not wishful to dispute any of Mr. Harrison's figures, which are undoubtedly correct. There is one

point, however, which I should like to raise, and that is, If we have such absolute confidence that we can so easily beat gas, and if, as Mr. Harrison has proved to us to-night again, we can light our streets more efficiently and more economically by electricity than by gas, why then do we not do it? There must be an answer to this. I have tried to give it myself, but failed. In certain districts, of course, we know gas is given away for street lighting, and with that kind of supply we do not wish to compete, but there must be towns and urban districts where electricity could be introduced with advantage, especially on the lines indicated by Mr. Harrison, and I should like to ask some of our friends here to-night why we do not see to our rights. Mr. Harrison in one of his replies stated that he found series tungsten lamps have 30 per cent. longer life than the high-voltage lamps. I should be very interested to know whether this statement is based on an all-round experience, or whether he has come across a single instance which he is quoting. My personal experience is that whilst low-voltage tungsten lamps may have a longer average life than high-voltage tungsten lamps, the series lamps certainly have not got a longer life than the parallel lamps, the most apparent reason being the difficulty of matching the series numbers. Mr. Sells.

Mr. H. C. CREWS: I think Mr. Harrison's paper marks the end of the rule-of-thumb era in street lighting. In future this will be done on scientific lines, but as vested gas interests, etc., have to be fought, progress on such lines may be somewhat slow. Now that we have very efficient small "metal" lighting units available we shall conquer. Let us, however, be fair and keep all costs before us—not merely current as against gas. The green curve C, for instance, of low-pressure inverted gas mantle, in Table VI., could be corrected by a suitable shade or reflector as some of the electric curves have been. On the other hand, the falling off in candle-power of all gas mantles is a very serious depreciation which our gas friends do not admit. Metal filament lamps are not liable to any such serious depreciation, and we have a great gain in that way. Mr. Crews.

DISCUSSION BEFORE THE BIRMINGHAM LOCAL SECTION.

(*December* 14, 1910.)

Mr. M. SOLOMON: As a good deal of the paper depends on the use of a particular type of reflector with the tungsten lamps at Marylebone, I think it would interest the meeting if Mr. Harrison would be good enough to sketch on the board roughly the shape of that reflector. [This was done.] I thank Mr. Harrison for the drawing, which makes the paper a good deal clearer in some points. Quite apart from the general character of the paper, it contains many very valuable data, especially the figures relating to the cost of maintenance of the various types of lamps. It is very easy to get from many sources figures giving the efficiencies of different types of lamps and to work out the cost per 1,000 candle-hours, but it is very difficult to get figures which give the Mr. Solomon.

Mr Solomon.

cost of lighting and trimming and all sorts of secondary operations which, as that paper showed, are a very considerable item in the cost of upkeep of lamps, and consequently in the cost of lighting. As regards the comparison with gas, roughly speaking, the paper shows that as a result of the conversion at Marylebone, the lighting effect was practically doubled for what was very nearly the same cost. I should like to ask whether these figures are based on an up-to-date system. As far as I can see, that is not the case, and the gas system with which the comparison was made does not represent the very best practice or the best result that could be obtained to-day by gas companies setting out to put in a well-thought-out installation—as well thought out as the electric installation described in the paper. I am quite aware that, as Mr. Morcom pointed out, our sympathies are very much on the side of the electrical engineer in these questions, but I think they are rather burying their heads in the sand and imagining that the gas-lighting engineers could not see them. I have taken out various figures at different times, taking for choice the figures put forward by the gas industry for their installations, just as I have taken the figures put forward by the electrical industry for theirs, and my conclusion is that it is a neck-and-neck race. Gas engineers can do lighting quite as cheaply, and in some cases more cheaply, and I do not think that electrical engineers do themselves any good by making out that they are ahead. I do not believe that they are. I believe that, cost for cost, the gas engineer could equal if not surpass them, and I think it is better to keep that fact in front of them rather than to try to claim a superiority in matters as to which the claim could not be maintained.

In regard to other points, some of the curves given by Mr. Harrison are rather astonishing to me. Take, for example, Curves II. and III. In Curve III. we have a comparison with Beck flame lamps. Curve A relates to a 10-ampere lamp with clear globe, and curve D to an 8-ampere lamp with clear globe. That is to say, the only difference shown by the curves is that between an 8-ampere lamp and a 10-ampere lamp. I have not worked it out fully, but, roughly speaking, the ratio of the mean hemispherical candle-power of the 10-ampere lamp to that of the 8-ampere lamp is three to two. In other words, by increasing the current 25 per cent. there results an increase in the volume of light given by the lamp of 75 per cent. I do not believe that if both lamps were using the proper carbons for 8 and 10 amperes respectively there could be this great difference between the two lamps. I do not dispute Mr. Harrison's figures, but there must be something which we have not been told in the conditions under which the two lamps were run. [Mr. Harrison : May I say here that these tests were made on purpose to demonstrate what a 10-ampere lamp would do with 8 amperes.] I do not think it is made clear. [Mr. Harrison : It is a comparison between opal globes and opalescent globes.] Mr. Harrison's reply certainly bears out what I think is the explanation—namely, that one of the lamps was using the wrong-sized carbons, as both curves to which I referred were for clear globes.

Mr. Solomon.

Therefore, if I might say so, the comparison is, in a sense, not a very valuable one. We do not want to test an arc lamp with the wrong carbons any more than to test a gas lamp which was meant to be burnt with a mantle, without a mantle. I might make a similar comment on the curves in Fig. 2, where we see a 12-ampere Excello lamp with a clear globe giving 300 per cent. more light than a 10-ampere Excello with an opal globe. There, I presume, the correct carbons had been used with each lamp, and it appears that the opal globe was such a bad one that it absorbed nearly two-thirds of the light given by the lamp. I think these facts rather mislead any one in studying the curves, because certainly the impression I got, and that which I think most people would get, is that the one represented the best to be got with a 12-ampere lamp and the other the best with a 10-ampere lamp. I would also like to ask Mr. Harrison whether the costs per candle-power per annum on page 41 were worked out for the 10° to 20° rays. If so, I think the figures rather misleading. I quite admit the importance in street lighting of considering the particular rays which we want to give a particular illumination in the street, but I think the figures are misleading if they give the cost per candle-power based on a special ray or group of rays. I have often urged that no comparison of lamps is of any value to anybody which is not based upon mean spherical candle-power. I quite admit that in this case it is a different question, because we are merely comparing the lamps for a special purpose, but are we comparing in all cases each lamp under the best possible conditions to give them the particular rays in the special direction in which they wanted them? I rather doubt it.

The whole paper brought out one point upon which I would like, in conclusion, to lay particular emphasis, and that was the supreme importance to the electrical engineer of designing, as Mr. Harrison had done, proper reflectors or proper globes for use with any particular source of light. We have to compete upon practically equal terms with the gas engineers, and shall not beat them unless we take every advantage of the means at our disposal to distribute the light in the direction in which it is wanted. Two or three years ago, when I was writing on this subject, I pointed out that what the arc-lamp engineer had done when the flame lamp was brought out was simply to use the spherical globe used for the ordinary vertical open-type arc lamp, and to think that that was good enough. It has taken two or three years for arc-lamp makers to find out that they ought to use the dioptric globe, which gave results such as those described by Mr. Harrison. I do not think for one moment that even in that respect the possibilities are by any means exhausted. The flame lamp is far and away the most efficient source of light electrical engineers have, and if proper reflectors and proper dioptric or other globes are used it can be made useful for almost all cases of lighting large spaces. The second point on which I should like to lay stress is the question of opal and opalescent globes. Mr. Harrison showed what enormous differences these globes made, and figures had been given at various

Mr. Solomon.

times which confirmed this. It is now almost a necessity for electrical engineers to go into this question of globes much more thoroughly than had been done up to the present. They ought to be able, when buying globes, to specify how much of the light they were to cut off. Lamp globes ought to be standardised, but at the present time it is not possible to tell whether they cut off 30 or 40 per cent., or even 60 or 70 per cent. of the light. Better globes could be got, and in any case engineers ought to know where they are. They devote a great deal of attention to the improvement of their light sources and to the standardisation of them, and then when they reach the maximum amount of illuminating power and efficiency, they put on an obsolete globe which cuts away half the light without even caring to find out how much they were losing or going to lose. Engineers are beginning to realise the state of affairs in regard to this question, but they ought to go into it very much more fully than they have done.

Mr. Chattock.

Mr. R. A. CHATTOCK: The paper before us is full of interesting facts and figures and will be most useful to electrical engineers who have to deal with the lighting of large areas. Mr. Harrison's figures have apparently been taken independently for the purpose of his paper, and on that account are specially valuable. Most of the figures I have seen before have been from interested sources, and it is therefore difficult to form correct conclusions on them. In this respect I am afraid that the sources of electrical figures are no better, generally speaking, than those of gas. Mr. Solomon has told us that he has come to the conclusion that gas and electric lighting are practically equal as regards cost. I cannot agree with this, and I think that Mr. Harrison's figures bear this out. On page 32, where the cost of high-pressure gas-lighting is compared with electric lighting, we find that gas would have to be supplied at 7d. per 1,000 cub. ft. in order to produce the same light at an equal cost assuming electricity to be supplied at 1d. per unit. It is difficult to tell at what price the gas companies are supplying gas for high-pressure lighting; but I think 7d. per 1,000 cub. ft. would certainly be far too low a figure to enable them to make a profit. Double that figure would be nearer the mark for most of the large gas companies, whilst 1d. per unit for electricity is a reasonable figure for a large modern station; in that penny would be included the cost of services such as installing the mains, etc. I was interested to see that in the discussion at Manchester Mr. Pearce stated that he was obtaining 1¼d. per unit for his street lighting, which covered the cost of the cables and so on. On page 32 Mr. Harrison mentions as an average figure 30 to 34 c.p. per cubic foot of gas consumed. I should like to ask whether this is a figure when the mantles are new or whether it is the average result for the life of a mantle. I think he has omitted to mention that with high-pressure gas the mantle very soon deteriorates, and the illumination falls off very much. Another feature of special value in the paper is the insistence on the provision of suitable reflectors for tungsten lamps. Engineers have not the time to design all the apparatus they use, but have to rely on the expert and the manu-

facturer. It is satisfactory to know that specialists like Mr. Harrison are taking this question up in a thorough manner. The reflectors and dioptric globes described seem to be a great advance upon what has been done hitherto. I am also glad to hear Mr. Solomon say that further advances will be made, because he is in touch with the manufacturing side, and he is possibly looking ahead with some special knowledge in that direction. Certainly I think that these reflector arrangements with tungsten lamps will solve the question of lighting side streets in cities. So far such lamps have the same disadvantage as gas, in lighting brilliantly in one place and leaving darkness between two lamps. Such reflectors, I suppose, cannot be applied to gas lighting because of the fumes, but this development will be greatly in favour of electricity. Mr. Harrison speaks of the unfairness of the Local Government Board in refusing loans to municipal undertakings for street-lighting purposes. Such action seems very unreasonable, for as a consumer street lighting is very attractive and very remunerative compared with the ordinary consumer; the load factor is good, and there are no expensive meters or other apparatus to instal, and the consumer is not likely to go off any quarter day without giving sufficient notice. I would suggest that if municipalities were to combine and bring this view before the Local Government Board the attitude of that body on the subject might be altered. To refuse to grant a loan for this purpose means that the municipality have to provide the whole of the money in one year and charge it on the rates. I cannot, however, agree with Mr. Harrison that a street-lighting load is better than a motor load. In the case of street lighting it is necessary to lay special mains for each lamp-post, which really constitutes a special service, and in many cases it would be necessary to lay special distributor mains in districts where possibly a general supply would not be taken, which would occur in outlying districts. In such cases there might be a very small return on a considerable expenditure of distributing mains. A motor load would have practically the same load factor, could in most cases be supplied off the existing distributors, and would load up the station more efficiently than street lighting. I should say that the two classes of load would be about equal in the benefit to the supply authority. Mr. Chattock.

Dr. W. E. SUMPNER: The paper is full of valuable statistics and will be useful for reference. One of the main points raised is the improvement brought about during recent years in the distribution of the light given out by various sources. This improvement has come about partly by design in regard to the construction of globes, reflectors, and so on, and partly by accident. It was unlucky that the electric light mostly used hitherto for street lighting distributed its rays in a way least suitable for that purpose, while the glow-lamp, the distribution of whose light is most suitable for street lighting, has been used for interior illumination. What is wanted for outdoor lighting is a lamp giving its maximum candle-power in a horizontal direction or nearly so; what is wanted in interior lighting generally is a light whose Dr. Sumpner.

Dr. Sumpner.

maximum candle-power is downwards or within 45° of the vertical. The former is characteristic of the glow-lamp which is used for interior lighting, and the latter is characteristic of the arc lamp which is used for street lighting, so that so far as distribution is concerned each light has been used for the purpose for which it is least fitted. But owing to recent developments the position is now greatly altered for the better. The invention of the flame arc lamp, by enlarging the size of the brilliant area, has much improved the distribution, and the flame arc lamp is not only very much more efficient in the production of a quantity of light for a given quantity of electricity, but also distributes the light more efficiently. The most important development has been the improvement of the glow lamp. By the introduction of the tungsten filament we have not only a lamp which will compete with the ordinary gas lamp in interior lighting, but also one which is cheap enough for, and whose distribution is just what we want for, street lighting. It has the advantage over its gas rival that it is perfectly clean and remains clean. This means that a reflector can be used, which will retain its efficiency. Mr. Harrison has pointed out how reflectors can be constructed and used to the greatest advantage. I am rather surprised that the particular point Mr. Harrison has alluded to about the reflector was not foreseen. The enamelled zinc reflector sends off most of its light by diffusion, and the theory of regular reflection does not apply. The essence of diffusion is that the light is sent off in fixed directions dependent on the surface of the reflector and not on the way the light falls on the reflector. What is wanted is a reflector shaped so that it will look largest from the point to which the light has to be sent. An ordinary reflector such as those over the glow lamps in this room throws the light mostly downwards, but if we wanted to send out the light in a horizontal direction by a reflector placed above the lamp, the best thing to do would be to turn the reflector upside down, so that the cone of the reflector pointed downwards to the lamp. There is one criticism I should like to make on the paper. It is a very old criticism, and is true of many papers. No comparison between lamps is worth anything if it is based simply on candle-power, and this is particularly true when one compares glow lamps with arc lamps. The candle-power of the arc lamp is always given as its maximum candle-power, and the same with the glow lamp. But if the total quantity of light given out by the glow lamp is represented by ten times its maximum candle-power, the quantity of light given out by an arc lamp (using the same units) is represented by about four times its maximum candle-power. Thus there is a factor of 2½ to bear in mind in making any comparison. If one has a glow lamp giving 1 c.p. per watt, and an arc lamp giving 5 c.p. per watt, it is not true that the arc lamp is five times as efficient as the glow lamp. It is only true that the arc lamp is about twice as efficient. All these points have to be borne in mind in comparing lights of different kinds, and it ought to be borne in mind in papers such as this. I know it is very difficult to do so and involves a great deal of work, but one must bear in mind that the cost per candle-

power per annum, although the phrase people normally use, is not worth anything, and is not necessarily the true measure of what the light costs. Mr. Sumpner.

Mr. A. E. ANGOLD: I wish to endorse the remarks of the previous speakers as to the value of the paper, and ask Mr. Harrison a question regarding the candle-powers. I presume the figures given are for the British standard, and not on the Hefner standard. Also, that all the figures given to compare the efficiencies of the various arc and incandescent lamps all refer to angles between 10° and 15°. Unless this latter point were emphasised all through, it gave rather a wrong impression as to the comparative merits of tungsten lamps and arc lamps for other purposes than street lighting. When I see statements that some types of arc lamps are not so efficient as tungsten lamps, I wish to emphasise the fact that for shop and workshop lighting the problem is quite different, and that comparisons on the angles between 10° and 15° are in these cases of little value. On page 32 Mr. Harrison gives some tables on this question of efficiency, and I think what is given there rather emphasises what Mr. Solomon has said about getting the conditions as nearly equal as possible. Otherwise there is some danger in making comparisons. If we are going into the question of costs it is not right to compare a 12-ampere or Excello lamp of 460 watts with an enclosed lamp of 460 watts. The lower carbon and trimming costs of the enclosed lamp permit of a larger expenditure of energy, somewhere about 600 watts for the same total running costs, and with such an increase of energy the efficiency of the enclosed arc is much improved. Therefore I think these matters should be taken into consideration, and the value of the figures given in the paper would be somewhat disturbed because the comparisons are not even. The least efficient lamp was put under the least efficient conditions, as the wattage was too low for that class of lamp. Mr. Harrison has said something about the enclosed flame and the ordinary flame arc lamps being used with the higher grade carbons recommended by the makers, and has drawn comparisons between one of the latter—viz., an Excello lamp and a magazine lamp. The Excello lamp uses a higher grade carbon than the usual magazine lamp, inasmuch as the carbon for Excello lamps has to have a metal core, and is usually made with a good class body, so as to emit a good, steady light, and permit the using of a fair proportion of the salts necessary to give the yellow flame; whereas in the class of magazine lamps which Mr. Harrison refers to carbons are used with a cheaper body, and this necessitates a small quantity of the salts, or else the arc could not burn steadily. Consequently the magazine lamp of this type is less efficient than the ordinary flame lamp. It is possible, however, and it is the general thing with some magazine lamps, to use the same class of carbon body and proportion of salts as in the Excello lamp, but as the metal core is not required in a magazine lamp the carbons are, therefore, considerably cheaper. The comparisons between the total costs of different systems of electric lighting will, I think, be considerably modified if the points I have mentioned are taken into consideration. Mr. Angold.

Mr. Angold.

As to the question of reflectors for throwing light up and down the street, has Mr. Harrison done anything with regard to the question of throwing a still greater proportion of light up and down the street rather than across the street? I understand that the reflectors Mr. Harrison has sketched are intended to make use of that light which would be normally thrown upwards, but has anything been done to get some of the light which would be thrown across the street and use it for throwing it down the street? As to the question of opal globes and the bad globes which have got into use, it is only fair to say that a large proportion of the arc lamps used for shop lighting are, unfortunately, not for lighting the shops, but for dazzling the customers. That is why so many of these globes found their way into use. There is no doubt that what is called a bad globe for the purpose of the paper is usually the one that looks the brightest. Of course we can get a bad glass which absorbs the light and shows nothing for it, but a dense opal glass looks the brightest, and I think that is why so many of them have come to be used.

Mr. Morcom.

Mr. R. K. Morcom: I should have very much liked somebody representing the interests of the gas world to have been present at this meeting. If such a representative is present I would like him to give us his views, because, after all, we are challenging gas figures, and are trying to prove that electricity is now at least as cheap as gas, if not cheaper. It would, therefore, be of the greatest interest to us if any one could come forward on behalf of the gas interests to discuss this question with us. As I see, to my regret, however, that no such representative is amongst us to-night, I think, after the very complimentary remarks from all sides as to Mr. Harrison's address, there is very little left for me to say. I am pleased to see that the discussion to-night has brought out one or two exceedingly good suggestions, especially the one recommending standard specifications for opal globes, and I sincerely hope that these suggestions will be adopted in future. The discussion which has taken place on this paper has already been a long and more extended one than our usual discussions, and Mr. Harrison will have his work cut out for him if he endeavours to answer now all the queries and questions which have been put before him.

Mr. Harrison.

Mr. Haydn T. Harrison (*in reply*): I quite agree with what Mr. Bailey said concerning raising the degree of illumination of our streets. The traffic in our streets has grown in a much greater ratio than the illumination, and there is no doubt that the increased traffic does sometimes demand a much higher illumination than probably many examples mentioned in this paper. As we cannot control the speed of traffic, the lesson should be brought home to the municipalities that the illumination which they can control should be increased, and I think the police do help us all they can: they are always crying out for more light—but municipal councils fear the increased expenditure they think will be necessary in order to obtain it. I think Mr. Bailey has shown one of the ways to obtain this increase by the manner in which it has been done in Cheapside. Unfortunately the new system

Mr. Harrison.

of light has been installed in Cheapside so lately that I have not been able to make any tests there, and I was hoping that Mr. Bailey would give us some of the figures. I do not know what the minimum illumination is, but there is no doubt it is very high. In London particularly it is essential that more money be spent on the lighting of some of the more important streets. As regards the question of glare, Cheapside is a very interesting case, because Mr. Bailey has installed centre lighting there. Two or three other speakers to-night have also mentioned centre lighting. I am not altogether in favour of centre lighting myself. It is good for the pavement and it is good for the pedestrian, but I do not consider it is altogether good for the drivers of omnibuses and other people who are mounted rather high and have these lights in their line of vision the whole time. Mr. Sparks brought up one of the most important subjects there is at the present moment, namely, the getting out of a standard specification for street lighting. The specifications that we have to work to are very few, and in some respects far from satisfactory. It is only the last year or so that we have had anything specified, except so many posts at such and such a height, put up with so much current available; as to whether that current produced any light or not the specification never said; but it was supposed to do something in that direction. The question of a standard specification is rather a difficult one, because the gas industry must be considered. It is a very doubtful thing whether if we as an Institution were to draft a specification it will be generally adopted unless agreed upon by all the parties concerned; therefore I think an independent society should finally approve the specification. That society really ought to be, if they will only study the subject sufficiently, the society to which the surveyors or city engineers generally belong, because it is they who have the street lighting under their control. Unfortunately we all know that very few surveyors have made any study of the subject. They have followed in the footsteps of their forefathers—so many posts with lamps on them to the mile, or something of that sort. They are beginning to consider the matter, and many of them are joining the Illuminating Engineers' Society, and therefore I hope they will probably learn in time that so many posts to the mile is not the only consideration in street lighting. I was glad to hear several speakers say that 1d. a unit is on the high side. I know it is, but, on the other hand, there are many municipal engineers here to-night who if they told their committees that they wanted to supply current at, say, 0·75d. for public lighting, would be told they were giving it away, because the committees do not appreciate the advantages which I have shown in the paper that occur with street lighting. The gas companies have appreciated it first and taken advantage of the very excellent advertisement.

In reply to Mr. Seabrook as regards central lighting for important streets, I quite agree that it is good provided the streets are wide enough and the lamps are placed high enough, but there are very few

Mr. Harrison.

important thoroughfares even in a city like London that are as wide as Oxford Street for instance, and as some of the main arteries are narrow central lighting must necessarily mean spare wires, fixings for which cannot always be obtained on private property. As this also applies to brackets, which is often a good system of lighting, it would be an excellent thing if some Act were passed to facilitate obtaining such fixings. With reference to Mr. Seabrook's remarks concerning the cost of Oxford Street lighting, both the illumination and cost are based on the posts being the maximum distance apart, namely, 200 ft. Many of them are much closer and therefore the cost is higher, but it would have been misleading to give this higher figure when comparing on the minimum illumination basis. This brings me to Mr. Seabrook's remarks concerning minimum horizontal illumination as a basis for comparison, and he will see from my paper that I do not consider it the best criterion, but where a comparison of various systems of lighting, differing in nearly every detail, is being made, it is the only means by which every factor can be brought under one figure for the purpose. Personally I prefer to know the candle-power of the lamps at various angles, the height and distance apart of same—in other words, the factors which go to make up horizontal illumination.

Mr. Vignoles must have missed the fact that I mentioned the question of the Local Government Board and loans in one paragraph of the paper; for the one example of Grimsby where the Board sanctioned the loan there are many cases where it has been refused. That is one of the details which has held back electric street lighting more than anything else in this country. I cannot understand why Mr. Vignoles likes a large diversity factor. I believe it was Mr. Mordey who some years ago used the word "seeing" capacity. If we have a large diversity factor, that is to say, if at one moment we are surrounded by objects illuminated very highly, and we pass from that into a position where we are surrounded by objects illuminated to a very slight degree, we cannot see those objects at all until our eyes have got out of the condition they got into on account of the high illumination. Therefore, as Mr. Mordey said, we have no seeing capacity in that way. The only way to really make people see in a low illumination—and of course side streets because of the cost cannot be highly illuminated—the only way to make them see well under those conditions is to keep them away from the degree of high illumination. I think it was Mr. Morris who pointed out that it was very much better if the people did not see any lights at all. We could often reduce the illumination of a street to one-tenth, and people would see better, provided they never saw the lights. Then Mr. Vignoles asked why Marylebone adopted two lamps. If we remember, Marylebone was one of the first to start this scheme or to work on the scheme when the tungsten lamp was first introduced, and a 240-volt lamp taking a very small current was hardly a satisfactory lamp to introduce into these streets at that time, so that they used two lamps in order to be able to put two lamps into series. It has

Mr. Harrison.

proved the right policy not only on account of life of lamps, but for the reason he mentioned, namely, when we have two lamps in one lantern the effect is distinctly better. Mr. Trotter misunderstood the remarks in my paper about the effect of increasing the height of the lights in Baker Street to 20 ft., namely, that it would increase the illumination by 50 per cent. What I said is that I do not think the people would appreciate the extra 50 per cent. I do not say that they would object to the height being increased, but I do not think the people would appreciate the fact that the illumination was increased. Mr. Trotter and several other speakers have called attention to the importance of the lighting of small streets. It is the small streets that do require a lot of very careful consideration. The origin of street lighting was the reduction of crime, that is to say, to prevent people being murdered or to having their pockets picked, and in order to prevent that, at least to a certain extent, lighting of the streets was started. It is in the small streets, the dirty neighbourhoods and suchlike places, that murders and burglaries occur. Nowadays you will find that shopkeepers in the main streets want to attract people by the warmth of the lighting in their district, but it must not be forgotten that when the shops are closed, the traffic still remains and the police still have their duty to perform, therefore the shop lighting can only be an addition to, not in place of, the street lamps.

As regards the side streets, attention should be given to the subject, but unfortunately what has to be done will have to be done at the minimum cost, as the improved illumination must be obtained without increasing the rates. Mr. Gaster seemed rather down on surveyors generally. I think he was too severe on them; surveyors have a lot to do; they have a very big diversity factor of work. If they have to know all about illumination, and all about drainage, and all about road-making, and all about everything else of that sort, of course they must know very little about any of them. I do not expect they will ever have time to learn the whole science of street lighting, but what I do think they might learn one of these days is that they can get information on the subject, which will greatly assist them to carry out their work more satisfactorily. Mr. Cooper asked what I mean by candle-power. If he looks at page 46, towards the end of the paper, I call attention to this difficulty and point out that in the table the candle-power of a lamp is taken as the candle-power of those rays which penetrate to the point of minimum illumination, which is generally those between 10° and 15° from the horizontal, and by a lamp I mean the source of light, its rays being as measured in the streets with all globes, reflectors operative. For instance, a 12-ampere Excello amp with a dioptric globe has a candle-power of very nearly 4,000. Therefore the cost of that comes out as one of the very lowest, but if the mean hemispherical candle-power is taken the cost per candle-power will be very much higher. But the mean hemispherical candle-power is of no importance to anybody for street lighting because we want the high candle-power rays approaching the horizontal.

Mr. Harrison.

The other point referred to by Mr. Cooper, namely, measurement of candle-power of a lamp having large illuminating sources such as reflectors or diffusing globes, does not affect the figures in this paper, as, the measurements being made in the street, the distance of the photometer from the source of light was sufficient to eliminate this error. Thus it is taken that the candle-power of the light source is that which produces a definite illumination at a distance. I have found that a considerable error is likely to occur if the candle-power of a light source having a large area is calculated from an illumination measurement taken nearer than, say, 20 ft. unless an allowance is made. Mr. Shaw said that he is able to do his street lighting at Worcester at less than £204 a mile, but he must remember that he has only about 44 posts to the mile, whereas in Marylebone, even in the least important streets, they have 65 posts to the mile, and that makes a considerable difference. I am very glad to have the figures of his capital cost per mile as they prove that conversion can be carried out at a low cost. Mr. Morris's tests are very interesting indeed, and they corroborate to a large extent what one would have expected to find. I have always maintained that if a lamp is adjacent to a highly illuminated white surface the effect of the glare is considerably reduced—in fact, if you get far enough away from a lamp in front of a white surface, take for instance a tungsten lamp, you cannot distinguish the light source from the surface.

I was very glad to hear Mr. Kenelm Edgcumbe support Mr. Sparks' suggestion of appointing a committee, as Mr. Edgcumbe is one of those who realises that light or illumination can be measured, and therefore produced and sold to specification. If this Institution only leads the way by showing how a specification, fair to all parties, can be drawn up it will have carried out an excellent work. Mr. Boot's remarks not only emphasise my point as to the small extra expenditure incurred in generating expenses, by undertakings taking on street lighting, but also prove the high value such lighting has as an advertising agent, which value the gas undertakings, being fully aware of, seem to appreciate. Mr. Dow's remarks support the importance of the light source for street illumination being placed as high and as close as possible ; the fact that this means smaller units should not allow of the principle being lost sight of, but should rather tend to uniformity as regards height and distance with various sizes of light units depending upon the importance of the streets. The question of surface brightness of surrounding objects is a somewhat difficult one to tackle, especially in London where all surfaces rapidly become dark in colour ; even if they were white, I doubt if much good would result by whitening the surfaces, as their brilliancy during the hours of daylight would tire the eyes and probably reduce their seeing efficiency at night.

Mr. Fedden's remarks *re* cost of cleaning of large lanterns such as are used for gas depends largely on the make of lantern ; some, which

Mr. Harrison.

are provided with suitable doors, are more easily cleaned than the small lanterns with one door. The capital expenditure, mentioned on page 26, of £3 per post converted included everything from opening up the ground to switching on the light. Each post is provided with a double-pole switch fuse, the service cable being twin lead covered and protected with paper insulation. It is not possible to give the figures for gas corresponding to the table on page 27 as the work was previously carried out by a contracting firm at a lump sum per annum. As regards the lighting hours, these are the same as before with the gas, but the watts given in the table are those designating the lamps at the time of conversion, whereas the actual consumption is less owing to the improved efficiency of the lamps, and the fact that they are run slightly below the stated consumption. Automatic switches are not used. The charges B and C have been reduced, as it has been found that one man can deal with more electric lamps than was possible with the gas lamps.

The facts which Mr. Wilkinson points out, namely, that the horizontal illumination near the lamp is reduced by increasing the height, is, in my opinion, a great advantage as it reduces the diversity factor; the increased illumination at corners may be necessary, but it should not be gained at the expense of comparative darkness directly the corner has been turned. Curve V. was given at unit illumination for convenience when multiplying by a factor proportionate to the candle-power. The tests shown in Curve III. were made on a direct-current lamp; there is no doubt that the different degrees of opalescence of globes considerably affect the shape of the profile curve, as also does the height of the arc relative to the economiser in a V-type flame arc lamp. The point raised by Mr. Kilburn Scott *re* centre posts is a very important one, and should be carefully borne in mind. I agree that brackets where they can be used are preferable to either posts or span wires; the suggestion *re* reflectors behind brackets is one which should certainly be adopted where the space behind the lamp is available for the purpose, but it should be wedge-shaped and brought as close to the lamp as possible. Mr. Sexton's remarks *re* photometery I have dealt with when replying to Mr. Cooper. I cannot agree that there is any impossibility in measurement of candle-power (within, say, 5 per cent.) provided any error due to large area of light source is practically eliminated by distance or any reflection due to surrounding objects is avoided. In reply to Mr. John D. Mackenzie, the angle at which the gas lamps were measured was about 30° from the horizontal. The electric lamps were tested at the same angle, and further tests on them at 20° gave almost identical results. The effect of dust on the Marylebone reflectors is not allowed to become noticeable, as the reflectors and lanterns are cleaned twice a week. My experience goes to prove that the upkeep of tungsten lamps or gas mantles is very similar in cost, but attention to burners used with mantles is more than lamp cleaning if they are to be properly maintained.

I cannot agree with Mr. E. P. Hollis that nobody in this country

Mr. Harrison.

has attempted to reason out the basis on which a street-lighting specification should be prepared. Mr. Bradly and Mr. Abady have done some excellent work in this direction, and I myself have written articles on the subject, but I do not consider it comes within the scope of this paper, beyond the proof of the need of such a standard specification; nevertheless, Mr. Hollis's remarks are of considerable interest. I agree with the bulk of them, but not with the statement that illumination cannot be measured sufficiently accurately for the purpose. I consider a 5 per cent. degree of accuracy to be quite near enough. I rarely find that observations carried out by different observers at the same time but on different instruments vary to this extent; the candle-power of lamps often varies from minute to minute to a much greater extent, therefore for comparison purposes tests should be taken at the same time. The question of whether the results are to be stated in candle-power or illumination is only a matter of convenience, as all photometers are primarily illumination photometers. The direct measurement of minimum illumination in side streets is generally impossible owing to it being too low, but it can be ascertained by measuring the candle-power of the rays on which it depends at a point nearer to the source of light. As regards the reflection from walls, etc., I prefer to use a photometer which avoids rays derived from this source, as I consider it would be unfair to allow it to interfere with the comparison of light sources under competition.

In reply to Mr. S. L. Pearce, I am glad that he agrees with Dr. Louis Bell and myself; we often have to take the position of street lamps as we find them, and improve the illumination as best as we can. As regards the use of two lamps in series at Marylebone, it must be remembered that at the time this work was carried out the lowest candle-power, 240-volt lamp took 63 watts, and was not satisfactory as regards life, hence it was necessary to use two 35-watt lamps in series. This arrangement has proved very satisfactory, the life of the series lamps proving better than that of the parallel, and the cost of maintenance less.

As regards the treatment of charges at Marylebone, Mr. Pearce suggests that to settle on a lump sum charge and then ascertain amount available for payment of current is putting the cart before the horse. Naturally every commercial undertaking wishes to obtain the best price possible, and the fact that Marylebone was able to do the public lighting better and at a lower price than gas, and yet obtain 1·42d. per unit, is in itself proof that they could if necessary reduce their price, which in fact they did when it was necessary to expend capital on distributors in order to complete the electric lighting of the district. I do not agree with Mr. Pearce that the allotment of interest and sinking fund on cost of distributors laid for both public and private lighting is such a simple matter, as it is not easy to ascertain the relative demand, as the demand for private lighting is continually growing, whereas the public lighting demand once completed remains constant. The figures relating to

Mr. Harrison.

Marylebone are particularly complicated, as about half the lighting was connected to existing distributors, the cost of services, etc., being repaid over five years; in the case of the other half, new distributors or ducts were laid, the cost of all of which naturally will not be repaid in such a short period.

Mr. Pearce is quite right to call attention to the better ventilation resulting from the use of dioptric globes with flame lamps. This is so important that these globes are now being used of plain glass where it is not necessary to divert the higher candle-power rays. With reference to different lengths of gas mantles, this considerably affects the distribution of light, the longer ones being preferable for street lighting; they are also generally more efficient for a given consumption of gas than the short type. With reference to the measurements on which the horizontal illumination figures are based, Mr. Pearce is quite correct in stating that in my paper of 1905 I advocated 45° for the measuring screen, and he will be pleased to hear that all the measurements were made at that angle, the candle-power and horizontal illumination being calculated from these measurements.

In reply to Mr. J. Huth, I quite agree with him that illumination is most urgently needed during fog, but as the sun fails under these circumstances I am afraid any artificial means will always prove a very poor substitute. I do not need to justify any practice of measuring horizontal illumination as I very rarely attempt it, preferring to calculate it from candle-power measurements made in the streets, but horizontal illumination is the most convenient factor for comparison as it embodies all the other factors.

With reference to Mr. A. G. Cooper's remarks *re* enclosed arc lamps, the lighting efficiency of these lamps is so low compared to tungsten lamps that I find very few places where their use can be recommended, and would certainly not attempt to obtain long burning hours for one pair of carbons, as the reduction of light due to deposit on the globes is a serious matter.

In reply to Mr. Moon, I am surprised to hear that an average life of 2,000 hours has been obtained in 50 towns. I have had before me the figures relating to a much larger number than this, and find the average nearer 1,300; perhaps Mr. Moon's were all low-voltage towns using high candle-power lamps, and the allowance for premature failures was high.

In reply to Mr. Sells, I would point out the three reasons why electric street lighting is not advancing at the rate he would expect: (1) Gas has possession, and possession goes a very long way where lay contracts are the rule; (2) the obtaining of capital for street lighting is a difficult matter in the case of municipalities; (3) street lighting contracts are not generally split up; therefore, unless the electricity undertaking has mains in every street a considerable amount of capital has to be expended. With reference to Mr. Sells' remarks concerning the relative life of series and parallel lamps, I could give him several instances, but both Marylebone and Canterbury are very

Mr. Harrison.

striking examples of the fact that the thicker the filament the longer the life.

In reply to Mr. C. Crews, I think that unsuitable profile curves of light for street lighting are common to both gas and electric lamps, but it is much more difficult to correct the gas on account of the heat and necessary ventilation. As regards being fair, I think Mr. Crews will find all costs taken into consideration in my paper.

In reply to Mr. Solomon, with reference to the comparison between the illumination of the streets of Marylebone before and after the conversion of the gas lamps to electric, it naturally refers to the gas mantles in use at the time; these were exceptionally well maintained, and above the average to be found in many other parts of London. Mr. Solomon seemed to think the figures in the paper were prejudiced in favour of electric lighting; the gas journals which had criticised the paper seemed to think the same thing; nevertheless the figures of candle-power were tests made by Messrs. Alexander Wright & Co., and also those of Mr. Abady, since published in a paper before the Gas Institute, corroborated by the author's own tests. If Mr. Solomon is in the habit of taking figures put forward by the manufacturers of either the gas or electric industry, I think he will find that they are very rarely corroborated by actual measurements made in the street. But even taking the statements of the manufacturers as correct in both cases, we get 60 c.p. per cubic foot for high-pressure gas, and 8 c.p. per watt for certain makes of flame arc lamps; the ratio is much the same, and the relative results, though not the true actual results, would be the same. Mr. Solomon has misunderstood Curve III.; this is intended to show the effect of increase of current when using the same carbons, and the effect of various globes, both of which details I think are important. As regards the comparison of the Excello lamp, these tests were made on street lamps under working conditions. I think Mr. Solomon will find that such variations are quite common, depending on current density and class of globe.

In reply to Mr. Solomon's question *re* the tables, such as the cost per candle-power per annum, these charges where not otherwise stated are the candle-power at 10° and 15° from the horizontal as indicated in Table I. These are the important rays for street lighting; it is this figure which is wanted, and therefore it is the figure given.

In reply to Mr. Chattock, I would mention that Professor Morris's figures of 32 to 34 c.p. per cubic foot (high-pressure) gas are for new mantles; the high-pressure mantles opposite my office in London are so frequently renewed that I doubt if I have ever tested the same mantle twice; the reason I preferred to take Dr. Morris's tests is that he was able to measure gas consumption, whereas when testing in the street I have not these facilities. As regards Mr. Chattock's remarks *re* the comparative value of street lighting and motor loads, I think that as they both overlap the lighting peak there would not be much to choose between them if it were not for the advertising value of street lighting, provided it is carried out satisfactorily. I think Mr.

Mr. Harrison.

Chattock's suggestion that municipal authorities should combine in order to bring a more correct view of the position to the notice of the Local Government Board an excellent one, and hope it will not be allowed to drop.

In reply to Dr. Sumpner, I am sorry that he has confused the issue by introducing the question of mean spherical candle-power; as a figure it is worth nothing to an illuminating engineer who must know the profile of lighting in order to utilise the lamps to the best advantage; for that reason I have given the costs per candle-power at the important rays for the purpose of street lighting, which is the subject under consideration. I do not agree with Dr. Sumpner that spherical candle-power is difficult to measure now that the Ulbricht globe is available for the purpose, but I fail to see that the results of measurements made with it are of much value to any beyond the pure scientist. Dr. Sumpner was surprised that the correct form of enamelled reflector was not foreseen, but the exact ratio of diffusion and reflection of any surface has to be ascertained by experience, and Dr. Sumpner also appears to have overlooked a second factor, namely, the degree of illumination of the reflector, which in the case of street lighting often falls with the function of increasing area visible from the point where maximum candle-power is required.

Mr. Angold is right in presuming that the candle-power figures given are British and not Hefner. As regards the relative efficiency of carbons used in various lamps, this has been fully taken into consideration when calculating total costs, and the candle-power figures are those in actual practice; therefore, as one affects the other, the total result would not be much modified if one factor is altered.

As regards reflectors for throwing light up and down the street, the Marylebone pattern do this, but do not alter it across the street, hence the high efficiency in the up and down direction. I regretted with Mr. Morcom that nobody was present representing the interests of the gas industry, but it must be borne in mind that this was not a paper comparing gas with electric light, but comparing the modern electric lamps and sources of light with those available in the past.

The President.

The PRESIDENT: Mr. Harrison has given us a valuable paper, and I ask you to give him a most cordial vote of thanks.

The resolution of thanks was carried with acclamation.

MANCHESTER LOCAL SECTION.

INAUGURAL ADDRESS OF THE CHAIRMAN.

J. S. PECK, Member.

ABSTRACT.

(*Address delivered October* 28, 1910.)

Having recently returned from a trip to America, it has occurred to me that a description of the progress made there in certain lines of electrical work may be of interest to you, as indicating certain differences in the engineering practices of the two countries. The features which impressed me most were the enormous quantities of standard machines which were being manufactured and the great advances made in electric traction, but there are many items of interest in other lines, and I propose to take them up in order and comment upon them.

Electric Traction.—The traction department of an American manufacturing company presents a very different appearance from that of a few years ago, for while one still sees the usual standard type of tramway motor, there are also large motors for the enormous electric locomotives which are now being used by many of the main steam roads for drawing trains in and out of their terminal stations, and for hauling trains through tunnels. These motors resemble slow-speed engine-type generators more than they do tramway motors, and some effort of the imagination is required to realise that a 14-pole machine with armature 6 ft. in diameter is really a railway motor; while the sight of cranks, jack shafts, and connecting rods on electric locomotives is new to any one who is not closely associated with this work.

For tramway and light railway motors the commutating pole is regarded as highly desirable, and motors of this type appear to be as nearly perfect as it is possible to build any electrical apparatus. The use of the commutating pole has practically eliminated all flashing from brush to brush, while the wear of the commutator and brushes is negligible.

High-tension Transmission.—Several plants are operating successfully at 110,000 volts, and 200,000 volts appear much nearer than did 100,000 ten years ago. In fact, one of the best known transmission

engineers in America told me he was quite prepared to recommend 200,000 volts now, and was sure it could be handled successfully. With pressures of this order a generating station in the Manchester district could reach every large city in Great Britain; in fact, with 60,000 volts the Ontario Power Company is delivering Niagara power in Syracuse, 150 miles away.

The general tendency on very high-voltage lines is to omit protective apparatus for the transformers, and endeavour to protect the line. Apparently the most satisfactory method yet proposed for doing this is the use of the overhead ground wire. For circuits below 40,000 volts lightning arresters are almost always used. The electrolytic arrester is being almost universally adopted for all voltages above 5,000.

Turbo-generators.—In turbo machinery the tendency is towards higher and higher speeds. For 25-period work 1,500 revs. per minute is the minimum speed for all machines, regardless of size, while for 60 periods 3,600 revs. per minute is used up to about 2,500 k.w., and 1,800 revs. per minute from 3,000 k.w. to 15,000 k.w. Peripheral speeds of field magnets run up to 23,000 ft. per minute.

With reference to direct-current turbos, much greater progress has been made in Great Britain than in America, for while large numbers of very small machines are being built in America, the large ones are few, and in general of slower speed than are found here. One of the large manufacturing companies is advocating for direct-current work a high-speed alternating-current turbo with 60-period rotary converter. The alternating-current end of the rotary may be connected direct to the generator, so that it starts and stops with the generator, and no synchronising apparatus or transformers are required.

Transformers.—The majority of the transformers are of the shell type, whether made for 1- or 3-phase. The core type is used when the voltage is very high in relation to the capacity of the transformer.

Great care is taken with all transformers to eliminate all traces of moisture from the coils and core, and with high-voltage apparatus the oil is also thoroughly dried before being put into the transformer. It is becoming more and more the practice to ship the transformer, case and oil complete. This eliminates drying out and filling with oil on site, and most satisfactory results are being obtained.

Motors.—The manufacturing companies have been devoting a great deal of time and money to increasing the demand for electric motors. For years past they have been collecting information regarding the power required, cost of operating, etc., for all kinds of different work; and this information placed in the hands of the so-called industrial expert enables him to talk intelligently, and to push the use of motors for various classes of work. It is quite customary for a man to specialise in one particular class of this work.

Sewing machines, vacuum cleaners, phonographs, washing machines, coffee grinders, candy mixers, and numbers of other machines are driven by small motors. There is also an enormous demand for fan

motors of various kinds. One plant which I visited had been turning out fan motors at the rate of over 6,000 per month for the past year, yet by the middle of July their entire stock was exhausted.

Measuring Instruments.—The most striking thing in this line is the enormous quantities which are manufactured. In one plant which I visited, they were turning out 1,000 alternating-current watt-hour meters per day. These meters are beautifully made, and contain various adjustments and refinements not found on European meters, yet on account of the enormous output they are able to manufacture for much less than the same instrument could be made for in this country, in spite of the fact that the price of labour there is more than twice as high as in England.

While the greater part of the large electrical machinery work and practically all the electrical railway work is done by either the General Electric or Westinghouse Companies, there is the keenest engineering competition between them. As a result they strive not only for the improvement of shop methods, but for advances in the electrical and mechanical design of their apparatus, and to the development of new and improved types.

The prosperous condition of the large companies enables them to carry large engineering staffs, to support research and experimental laboratories, and to undertake the development of new lines of apparatus and of new electrical systems on a scale quite impossible for the manufacturers of this country.

A majority of the best known electrical engineers of America are associated with the manufacturing companies, and the high average quality of papers read before the American Institute of Electrical Engineers is due largely to the fact that these engineers take an active interest in the Institute, and bring before it in the form of papers the results of their experiments and calculations.

I propose now to discuss very briefly a few of the factors which influence the electrical manufacturing business and to point out some of the differences between Great Britain and America. The ones I shall refer to are:—

1. Technical education.
2. Labour organisations.
3. Municipal undertakings.
4. Governmental restrictions.
5. Consulting engineers.
6. High labour cost.

1. *Technical Education.*—I do not propose to discuss here the relative merits of the different systems of technical education which have been proposed, but, regardless of system, there is no doubt that Great Britain is far behind both Germany and America in the extent to which technical education is adopted; and by technical education I mean not so much the education of trade schools, as the higher theoretical training obtained at colleges and universities.

In Great Britain the general idea has prevailed that the proper way to make an engineer was to take the boy from school and put him in the shop, thus making a practical man of him, and the great success of British engineers and the wonderful development of Great Britain as a manufacturing nation seemed to give weight to this argument; but the rate at which other nations that have adopted technical education are overhauling Great Britain has forced from our manufacturers an admission, more or less reluctant perhaps, that technical education is a thing to be desired for an engineer.

Some fifteen or twenty years ago the "college engineer" was looked upon with grave doubts by the majority of American manufacturers, while the practical workmen and foremen did not attempt to conceal their contempt for the "college engineer" when he appeared in the shop, but the college man of America has made good; he has shown that he is not afraid of hard and dirty work, and he has demonstrated beyond question that the training received at college enables him to outstrip the man of equal natural ability who has not had this training.

To-day the manufacturing companies are competing for men before they leave college, and it is not unusual for practically the whole graduating class in some of the colleges to have positions secured before Graduation Day, and with salary enough guaranteed at least to pay living expenses. I saw an advertisement in one of the American College papers, stating that a telephone company was prepared to take a certain number of college men on a six months' apprenticeship course, at a salary of £12 per month. If at the end of six months they were satisfactory, they would be taken on the staff at salaries depending upon the positions obtained.

The American Westinghouse Company pays its college apprentices 9d. per hour; the Westinghouse Machine Company slightly more than this, and these examples are fairly representative.

The manufacturing companies also attempt to foster a spirit of loyalty in the young college men who pass through their works, as these men are often of great help to them in securing business when they have taken up positions with operating companies, perhaps in foreign countries. German companies also appreciate the value to them of the graduates from their works, and probably most of us realise the difficulty of selling British-made apparatus to engineers who have received their technical training in Germany. It might make a marked difference in our electrical export trade if some of the young Continental engineers came to England instead of all going to Germany for their technical training.

What do the electrical engineering firms of this country think of the college educated man? Go into the works of almost any large British manufacturing company, and you will find many of the best positions in the engineering departments filled by foreign engineers. Why? Certainly not because British manufacturers prefer foreigners, but because British educated engineers with the requisite training are

not available. Great Britain needs better education for its young men, and it is the duty of this Institution to do all in its power to promote this better education, and I believe one of the best ways to do it is to inspire our embryo engineers with a desire to obtain a thorough theoretical knowledge, in addition to a practical training, even though this may delay the time at which they can become self-supporting. Create the demand, and means will be found to meet it.

2. *Labour Organisations.*—The electrical manufacturer of America has never been seriously hampered by those restrictions which labour organisations attempt to impose upon manufacturers here, and if Great Britain is to improve or even maintain her position as a manufacturing nation she must demand the same freedom as her competitors in dealing with this problem. The manufacturer should have the right of employing such labour as he considers best suited to the work in hand, while every workman should have the right and should be encouraged to improve the quality of his work, and to increase his output, thus improving his position and his rate of pay. Without these rights the British manufacturer and his workmen will be terribly handicapped in competing for the open markets of the world.

3. *Municipal Undertakings.*—Municipal control of electric supply and tramways was never seriously undertaken in American cities, probably because the people took little interest in these matters, and capitalists, seeing the opportunities, were not slow to take advantage of them. To-day the tendency seems to be to leave this work in the hands of the companies, but to put limitations upon them, allowing them to make fair profits but insisting on good service and reasonable charges.

The policy of the municipal undertakings in Great Britain in accepting the lowest tender is in part responsible for the cut-throat prices which rule to-day. This practice of awarding to the lowest bidder is carried so far that business is often given to foreign competitors, and though comparatively little work goes abroad at the present time, it is probably due more to the fact that ruling British prices offer little inducement to the foreigners than to any spirit of patriotism on the part of the municipalities, while the constant fear of foreign competition keeps prices at an unremunerative level.

In America many of the large supply companies, traction companies, and especially the water-power companies, are controlled to a greater or lesser degree by one or other of the large manufacturing companies, and they offer excellent markets for electrical apparatus at reasonable prices. In general, the supply companies and the manufacturing companies are in much closer relation than they are in this country.

4. *Governmental Restrictions.*—Perhaps the greatest electrical development in America has been in traction work, and while a great part of this has been in the cities, there has been an enormous development in inter-urban railway lines—a field which has been scarcely touched in Great Britain, due to the expense of getting Bills through

Parliament, the jealousy of town councils, and the opposition of wealthy property holders along the proposed lines. Yet there is no doubt that high-speed electric railways through many parts of this country would be of great benefit to the sections served by them, and would prove great financial successes, provided excessive charges were not entailed in getting powers to build and operate. If the country once recognised the great desirability of electric inter-urban service, some way would be found for encouraging its extension by making it easier and cheaper to obtain the necessary powers.

5. *Consulting Engineers.*—The large electrical manufacturing companies in America employ specialists in all departments of engineering, and it is generally admitted that these men know more about their particular lines of work than the consulting engineer can be expected to know. Thus the consultant in his specification tells what he wishes to accomplish, and asks the manufacturers to say how they can best obtain the desired results, and what guarantees they are prepared to make.

In England the practice was for the consulting engineer to specify in great detail particulars regarding all the work to be done by the manufacturer. This was undoubtedly due to the attempt of the consulting electrical engineer to follow the practice set by the civil engineer, who, in dealing with many different contractors, found it necessary to specify exactly what was to be done by each, and how it was to be done. But in the manufacture of electrical plant the conditions are entirely different, and it is now becoming generally recognised by the more progressive consulting engineers that each manufacturer should be allowed great latitude in the design of his apparatus, as long as the specified results are secured. Undoubtedly consulting engineers can often be of great assistance to the designers, and where there is full co-operation between them, the most satisfactory results for all parties are likely to be obtained.

6. *High Labour Costs.*—In America the demand for labour is usually greater than the supply, and the rate of wage at least double that in this country. This condition naturally creates a great difference in the demand for labour-saving machines, and is in part responsible for the enormous demand for small electric appliances. Whenever labour can be saved by means of a machine the machine is usually installed.

Labour-saving devices could and will be used with advantage in this country to a far greater extent than at present, but the low cost and plentiful supply of labour does not make their introduction so imperative as in America.

NEWCASTLE LOCAL SECTION.

INAUGURAL ADDRESS OF THE CHAIRMAN.

C. FARADAY PROCTOR, Member.

ABSTRACT.

(*Address delivered October* 31, 1910.)

I have felt that the rather exceptional experience of having been sent with Mr. James Swinburne in 1881 to start a new industry first in France, and subsequently in England, France, Belgium, and Germany, and later again in Paris, has enabled me to form an opinion of the difference between English and Continental methods, especially as regards the adaptability of the hands to the work to be done. In the first place, the foreigner surpasses the English work-hand in general personal neatness, and orderliness in work, and especially so in elementary education. On the other hand, the English girl has more initiative, courage, and nerve to overcome difficult processes, but the lack of neatness necessitates selecting very young girls, who give promise of tidy habits, and carefully training them, but often the most elementary education has already been forgotten.

Since I sketched out the substance of this address, the interesting series of papers read before the British Association at Sheffield have come to hand, and I am glad to see many of them strongly support my argument that a more practical form of education is required. Sir G. Reid, in his short address at the British Association meeting, says publicly what I have often said privately, that the modern student's knowledge is too much of the nature of a "gramophone record"; the information is there, but the human aspect is missing, and I think in many cases the effort of acquiring knowledge has so benumbed the power of using it, that it is only useful as a reference or as a book would be. The present system tends to regard the successful passing of examinations as proof of the scholar's knowledge, but I contend that it only proves his ability to pass examinations, and the true proof of the efficiency of his education is the ability to earn a good living for himself and a social position somewhat better than that inherited from his parents.

Consider how rapidly a good engineering draughtsman or architect can take in the whole detail of a design and point out errors before the

quickest readers could possibly understand a tenth part of it, if described in writing, and how very few people are able to make even a tolerably good sketch. Every journalist is realising the value of illustration, but I am afraid that our schools still do not sufficiently insist on drawing being generally taught, but that they rather regard it as an extra. Sir John Gorst, in the address he gave at this College, said, " It is advised that more technical and practical instruction should be given to the children of our elementary schools by replacing the 'book schools' with what German educationists call 'work schools.'"

Mr. Blair in the early part of his paper at Sheffield referred to a case of a mechanical engineer with first-class honours finding it extremely difficult to obtain a post until he obtained influence to aid him. I can well understand the position. I have had to go through batches of letters from candidates applying for posts, and assist others in the same work, and even when a highly trained man is wanted, a long list of examinations successfully passed tends to depreciate the chance of success of the candidate, since it not only indicates a lack of practical experience, but shows a long experience at learning just how to grasp the particular information required for passing examinations without spending time on the many side issues that a less successful but equally studious man may have been observing, and which are essential in a man if he is to be of use in a factory. Again, a man who has devoted his energies to examination passing has obviously been gathering his information from books, whereas, in a factory, he will soon find that the process or processes he has to deal with are already far in advance of the best books on the subject, and his work will consist of a very close observation of the process (not books) and the noting of each slight alteration.

Another very striking point made by Mr. Blair illustrates the waste that goes on in connection with the training of engineers, from a certain number of whom he succeeded in getting particulars as regards their future. He showed that under 30 per cent. are at engineering work, and 70 per cent. are engaged in teaching. Employers are blamed for not taking advantage of the theoretically trained man, and indeed are accused of prejudice against him, but I think any feeling they have is far surpassed by the rather open want of appreciation often shown by the theoretical student for his practical associates either in the college or works, resulting in the breach between the practical and theoretical sections of a works which often leads to want of efficiency, especially in the theoretical departments. Personally I think this breach between the theoretical and practical departments accounts for the inefficiency of much of our present work.

In 1884, when I went to Lille to assist in the fitting up of the Lille factory, Mr. C. H. Stearn drew my special attention to having the platinum leading-in wires of the lamps clean. I have found that the highly trained student is apt to consider such a little question as dirt on a piece of wire as a matter for the foreman to see to rather than for himself to investigate. I had found it was possible to get the wires

actually sealed into the glass perfectly clean, and yet, when the lamp was finished, the wires in some cases were dirty, or at least black. By following the matter up, I discovered that the glass was being decomposed, and the oxide of lead in it was being converted into metallic lead on one pole, and on my reporting the discovery to Mr. Stearn, he pushed the experiment still further, and succeeded in getting indications of gas being given off at the opposite pole. I have mentioned this matter in some detail because I know of many somewhat similar cases where the want of a closer touch between the scientific and practical ability of a factory has caused heavy losses. For real economy or efficiency we must go still further, and have not only the practical and theoretical departments working together, but also the commercial department.

From a theoretical point of view I think education must consist of two primary processes, namely, the impressing of a picture on the brain, and the cultivation of the brain in such a way as to enable it readily to receive the pictures, and to call them to mind at will. Profitable education must consist of the opportunities given to the brain of obtaining records and the choice and permanency of the records obtained, but supposing we have a large collection of good records, they are of little use unless they can be called to the front at appropriate moments, and even then it requires another and I think a still greater faculty, namely, that of seeing how to fit in the various somewhat similar pictures or impressions in such a way as to make them of use when new conditions occur, and so enable the brain to form a new picture, and continually draw from its stock of records until what is called a completely new idea has been developed.

Let me take for example the present method of making an incandescent lamp. In *La Lumière Electrique*, April 30, 1892, M. Falcou drew attention to there being ten different methods of constructing incandescent lamps, and especially referred to a design of my own which, to a non-practical man, looks very like the Edison design, but which actually introduced a saving of many thousands of pounds per year. Every engineer knows that sharp corners should be avoided, especially when large differences in temperature occur, such as in castings, and the same also applies to glass work.

What I want to draw special attention to is the system that the brain has of adapting the various pictures or parts of them, one to another, until the idea is complete, and I contend that the overcrowding of the brain with records seems to crowd out the faculty of putting together the various ideas, or maybe the impression gets so permanent a set that it can only see the thing exactly as it was. I think, to some extent, this can be taken as an explanation why some inventors or originators are bad spellers, for they only have a general idea how the word is written, whereas the brain that cannot see another way of spelling is (shall I say for my own sake ?) wanting in originality. Of course, there must be a proper balance of ideas, or, I might say, intensity of the pictures, and I believe to a great extent the rapid

progress that other nations have made as compared with ourselves is owing to a better view of the ultimate object.

I am told that in Germany a clear understanding of the problem to be treated is regarded as of paramount importance. In France I know, from many professional friends, that one of the most difficult examinations that a professional teacher has to pass is that of lecturing to his examiners as if they were young students, thus being restricted to the most simple language. I cannot but feel that in some cases at home our lecturers assume that their audiences have a greater interest, or knowledge of the subject, than is often the case. America, again, is a most striking example. Their success, I consider, is due to their clear view of what might be called the meeting-point of every problem, namely, does it pay? The very suggestion of the word, I know, grates on the delicate ears of some pure scientists, or professional men, and yet even ½ per cent. greater efficiency in a machine, or the suggestion that a little bit of powder-like radium can have any superfluous energy, is of immense interest. Then why not also study how to show the rising generation, by a few simple pictures, all that we have so laboriously learnt, and thus leave their minds and brains clear enough to grasp the much larger field of knowledge that is every day opening up before them?

Many of my friends accuse, nay, even blame me, for finding imperfections in my own countrymen, but I maintain that it is by seeing our own deficiencies that we can hope to maintain the lead that we used to have in many industries, which is certainly less to-day than it used to be, and I am afraid has not been replaced by any new industry. Take, for example, America, who, although she pays 10 to 20 per cent. higher wages, can, and is, selling thousands of pounds' worth of machinery in England. Germany is not only selling large quantities of small electrical fittings, but also considerable quantities of heavy electrical machinery.

While in Paris I visited the paper-mill of a friend, and was much impressed by his mentioning that he bought scrap paper in England, was re-making it, and selling it again in England. From a Board of Trade return point of view it would increase our exports and imports, but is it economy? I tried to get a local paper-maker to take up the idea, but I found that the mill had been shut up because it did not pay.

We used to be large glass workers, but our workmen would not use our improved methods. The trade went to Germany, who did do so. When we wanted glass workers for lamp making, we had to go to Germany for them, and pay from £5 to £8 per week for a poor days work, with the result that we trained girls, who now, by the aid of machinery, do twelve times the amount of work. At first it was feared that the business of incandescent lamp making would eventually become a German business, and one English maker still imports large quantities of German-made lamps for the English market, but we can certainly claim to be selling a large quantity of English-made lamps

abroad. On the other hand, I think it must be admitted that Germany sets the pace as regards electric lamp bulb making. Of course, many millions of bulbs are made in England, but I do not know of any one being able to export them at a profit, and why not? Is it the labour or the capital? The materials are as near to us, and, I believe, quite as cheap. Some people suggest other reforms than a more practical education, and, indeed, one large manufacturer, who often advocates drastic reforms (at least as revolutionary as I want) has proved that even the long-established Continental business of telephone making can be wrested from the foreigner (who has the advantage of good wood supplies) and made at a profit in England; and I contend the secret is simply a good or real combination of capital and labour, theory and practice, backed, of course, by good commercial ability.

I have already expressed the hope that my hearers will not accuse me of depreciating the abilities of the Britishers, for nothing is further from my mind. When once stirred to action, I believe no nationality is more capable, either individually or collectively, of working either for its own good or that of the world in general. Gentlemen, the problem is how can we be roused up sufficiently to obtain a majority in favour of greater efficiency in life and learning.

GLASGOW LOCAL SECTION.

INAUGURAL ADDRESS OF THE CHAIRMAN.

THE POWER EQUIPMENT OF COLLIERIES.

SAM MAVOR, Member.

ABSTRACT.

(*Address delivered November* 8, 1910.)

In the address, which it is the duty and privilege of your Chairman to present, an attempt may be made to survey the various fields of activity of the members, giving a retrospect of past achievement, a review of the present position, and a forecast of future progress, or the address may be devoted to treatment of a subject or subjects of special local interest.

At a time within the professional or commercial career of many of us, the making of a general survey of electrical engineering was a brief and simple task, but developments have been so rapid, so varied, and so great in magnitude and importance, that it is no longer possible, within the limits of an address, even to touch their fringe. I therefore adopt the latter alternative and shall submit a few observations on a subject of intimate interest to this district.

As individuals we cannot now, as formerly, keep our information abreast of modern developments in every branch of electrical work. On the contrary, diversity of opportunity has had the paradoxical effect of driving us into specialisation.

Even when our profession is viewed from the standpoint of our Local Section the horizon is wide. This neighbourhood is fortunate in possessing a great variety of industries, and it is safe to say that the electrical engineer has points of contact with nearly all of them, and he has made himself indispensable to many of the most important.

An endeavour to make a comprehensive survey of electrical engineering in this district alone would be a considerable undertaking, and would cover ground which is already familiar to most of you. The time at our disposal will probably be most suitably occupied with a department of work which has large possibilities of expansion locally, and I propose to present some considerations on the application of electric power at collieries. The subject was dealt with some years

ago by a former occupant of this chair, but its sphere exhibits so many aspects that further examination of it may not be unprofitable.

I shall further venture to make references to, and comparisons with, Continental practice with which frequent visits to the European coal-fields have made me somewhat familiar.

The introduction of electric power has been an inestimable boon to many industries, but to none are its services of greater value than to coal-mining. This was quickly recognised, and few departments of electrical engineering have had so much attention devoted to them as this branch of work.

In recent years the demands for power at collieries have been greatly augmented. Formerly the requirements were only for ventilating, pumping, hauling, and winding. Now, developments in the practise of coal-mining, and in treatment of the product, have entirely changed the conditions in respect of power supply.

Acceleration of the rate of hauling and winding, especially in the deeper collieries, increased pumping, a higher standard of ventilation, the replacing of manual and horse haulage by mechanical means, and the introduction of coal-cutting machines and face conveyors, have all contributed to increase the power required in the mining and raising of coal.

The additions to the requirements for power do not end here. After delivery of coal to the surface a new set of demands is made.

Contrast the simple pithead arrangements of twenty years ago with the imposing structures, and the various and elaborate machinery included in the surface equipment of a colliery of to-day.

Competition in the market necessitates the supply of screened and washed coal of many sizes, and power is absorbed in treatment and improvement of the crude product of the mine. The screening plants, and the washeries in which Germans have taken the lead, and often by-product recovery plant in connection with coking ovens in which Germans have again taken premier place, in conjunction with the increased underground requirements, have introduced a completely new set of conditions in respect of the development and distribution of power at collieries.

The colliery manager is seldom a specialist in economical power production. On the contrary, his multifarious and exacting duties have prevented him from devoting adequate attention to the subject. He has been accustomed to consider power plant an unwelcome but necessary accessory to his mining operations, and knowing that whatever the cost in fuel, it is unimportant relatively to the advantages derived, he does not inquire too closely into the coal consumption. Provided the power plant unobtrusively serves its purpose of contributing to the enlargement and value of the output, and does not by breakdown assert its presence, the manager has been content. Extravagant fuel consumption is only noticed as an increase in the ratio of coal burned to the total coal raised, and it is swamped in other

fuel extravagance which the manager has neither the time nor the qualifications to investigate.

Under the changed conditions the cost of power at collieries which was formerly looked upon as relatively unimportant has by the increasing size of power plants become endowed with considerable absolute importance; further, stress of competition in the world's coal markets and rising wages at home impose the necessity of checking waste when located. As a result the coal owner and the colliery manager now realise that in dealing with the problems associated with power production the aid of a specialist is indispensable. The electrical engineer, whose scientific training and exact methods of measurement have enabled him to deal in detail with these problems, has established himself in the premier position in this department of engineering. To the electrical engineer, therefore, is often allotted the duty not only of planning the electrical arrangements, but of undertaking the whole scheme of power production and distribution.

A little has been done in modernising power plant at our collieries, but relatively only a little. The field for the power engineer is co-extensive with our coal-fields, and the present extravagance of fuel would be appalling if it were not the measure of our opportunities. It is unnecessary to give examples to illustrate existing conditions; you are familiar with them. It may, however, be recorded that there are collieries in England to-day yielding considerable outputs, where banks of boilers are installed underground, far inby from the pit bottom; the return airway and upcast shafts being used as flues.

The mechanical engineering of Continental collieries generally differs from ours in respect of the greater elaborateness and the style of the equipments. The scale of capital expenditure would in this country be considered ruinous; judged by our standard the extravagance is often profligate. Spacious and lofty power houses are the rule. Stained glass windows, ornamental balustrades of hammered iron gilded, plush curtains pendant from lacquered brass over the doorways, not infrequently decoration of growing plants and flowers, and attendants in spotless clothing of washing material, give a key to the style of modern Continental colliery practice.

The plant in appearance and finish is worthy of its surroundings. Generous provision is made of spare machinery, and one of the most noticeable features, common to all industrial equipments in Germany, is the profusion of automatically recording and measuring instruments.

The same scale of extravagant treatment is applied to the power using plant; similarly the elaboration of detail is apparently much overdone.

As with the *materiel*, so with the *personnel;* the colliery manager's standard of qualification is much higher than in this country, and he has at command a highly educated staff of mechanical and electrical engineers.

The methods of colliery finance, the lower rates of wages, the longer working hours, and the higher prices obtained for the pro-

duct, give latitude in expenditure which few of our collieries can afford.

The capital expenditure on Continental collieries not unusually amounts to £1 sterling per ton of coal produced per annum. In this country the average is about 10s. per ton per annum. The difference is in some cases partially due to the greater difficulties of mining, but it must be chiefly attributed to the more expensive scale of equipment. It is quite certain that a similar scale of expenditure can rarely be adopted in this country.

While there is much of suggestion for us in the Continental practice, there is also much of warning, especially in respect of over elaboration of detail. Multiplication of appliances can only be justified by economies of fuel or of labour, but it is not the case that in the elaborately equipped Continental collieries the output is handled by fewer men than in this country. The contrary is true.

The output of coal per man underground and on the surface is, in corresponding seams, higher here than abroad, and it is a constant matter of surprise to foreign visitors that the large outputs of many of our collieries are obtained with plant apparently inadequate, and are handled at the pit-bottoms and pit-heads by numbers of men that elsewhere would be considered quite insufficient. The explanation lies in the fact that while Continental colliery managers are engineers rather than pit-men, our managers, although less highly educated, are better practical miners, and plan their operations and coal-handling plant with the primary view of saving labour.

If our Continental friends have been extravagant in their power equipment we have as surely been parsimonious. Between these extremes there is ample room for a middle course, and much may be done at our collieries without risk of exceeding the limits of prudence.

The diversity of conditions under which power must be produced and used at collieries gives ample range for variety of treatment, and affords many opportunities for the exercise of initiative and the application of experience. It is beyond the scope of this address to make detailed reference to any of the problems of the economical generation and utilisation of steam, or to the place which may be taken by large power gas engines at coking collieries.

Recent progress has made available an almost embarrassingly wide choice of plant and appliances, designed to effect economy of fuel, directly in steam raising or indirectly in steam saving. So far as collieries are concerned, no line of development has been so important as that of turbine machinery, and this branch only will be noticed.

Turbine machinery of to-day owes its position to association with electric generators and motors, and it is about to repay handsomely its debt to the electrical engineer, by enormously increasing the demand for turbo generators and high-speed motors.

The turbo blowers, and turbo air compressors of large size, and the turbo pump of all sizes now at work, and the results obtained from them, render it certain that reciprocating machines for the purposes

indicated will be as completely swept off the field as have reciprocating engines of large size for electric generators.

It is to be regretted that the Germans, to whom this country gave a lead in turbo machines, have been allowed to go far ahead of us. That they have done so is beyond question. The fact is patent to those who have seen the latest developments in Germany. Turbo air compressors, in sizes up to 16,000 H.P., are being sent from Germany to the Rand, and rendering obsolete the large reciprocating compressors to which the leading makers in this country still cling.

The extent and character of the German work in mining turbo pumps is well known.

In condensing plants turbo pumps have ousted reciprocating pumps in the latest power stations. The new practice is to mount on the same base, and couple together, a turbo circulating pump, a turbo air pump, and a steam turbine to drive them, and a high-pressure turbo pump is also adopted for feeding the boilers. In many stations not a piston, not a crank, not a single piece of reciprocating machinery is at work; it remains idle as a contrast with the beautiful simplicity of the rotary machines, only until the valuable space it occupied is required for extensions of the turbo generating plant, with its turbo accessories. While high efficiencies are claimed and undoubtedly obtained from the newer applications of turbo plant, it is not to be supposed that every difficulty has been solved. A high standard of excellence in respect of efficiency and durability has been established by long practice in reciprocating appliances, and the new rival must confirm its claim step by step before receiving general acceptance. Our enterprising competitors are ahead of us in this department of engineering, and they are increasing their lead; the cream of the business in foreign markets is their reward. In France, for example, where there is a decided preference to purchase from Britain, our turbine machinery is considered out of date, and plant of this type, other than that made in the country, is imported from Germany. Makers of turbine plant in this country may be reluctant to admit that they are lagging, but the fact is that we are losing business in neutral and even friendly markets, because the purchasers believe that our practice is not sufficiently advanced.

It is true that the conditions under which new types of plant are developed and exploited in Germany and in this country are different, but these cannot be dealt with here. The statement must suffice that in a new branch of engineering which has experienced magnificent expansion, we were in front, and our present position is in the rear.

It is not suggested that British makers are not following, but their present position is that of followers, not of leaders, in this important field.

The problem of improving an existing colliery plant and reducing fuel consumption is much more difficult and complicated than that

of designing a power station for a new colliery. But in the case of an existing colliery the engineer had the advantage of available data as to the actual demands for power by the various services; whereas in an undeveloped colliery the requirements are to a considerable extent problematical and must be estimated. In dealing with old collieries the financial factor is frequently the predominant one, and the replacing of obsolete and uneconomical machinery may be commercially impracticable. When the colliery has a short life, or when the correction of past errors is too costly, the enduring of current waste is often rightly preferred to the incurring of capital expenditure, and all such cases must be approached with great caution.

At collieries of considerable size, where the present and prospective financial conditions warrant drastic treatment of fuel waste, or where additional power is required, the mixed pressure turbine is rapidly taking the place to which its characteristics so singularly well adapt it, and a wide expansion of its use is inevitable. Within the limits of its range of application it provides a most valuable means of reducing fuel consumption at collieries. The capital cost of the mixed pressure turbine, with its condensing accessories, is, however, relatively high, and will be prohibitive in cases where the value of the fuel is so low that the saving effected is insufficient to balance the capital charges on the plant.

Frequently the problem of reducing fuel consumption can be associated with the provision of additional plant for machine-mining and other purposes. When the mixed pressure or the exhaust turbine is adopted, its tendency to eat its own tail is to be noted. An ample supply of exhaust steam from uneconomical engines may at first be available, but the electric motor has a way of displacing these engines, and as the electric load increases the supply of exhaust steam diminishes.

Whether the power supply contracts fairly favourable to the colliery companies which are now current can be renewed on the same terms remains to be seen. The fact that at many collieries certain classes of fuel, and at others gas from coking ovens, are merely by-products of little or no saleable value, must continue to restrict the sphere of supply companies so far as collieries are concerned.

For new collieries, where it is desired to prove the seams, and to carry out the initial stages of development at the lowest capital expenditure, the supply of power at a moderate price from an outside source is a great boon. Power companies have also enabled many collieries to avail themselves of the advantages and convenience of electric driving without incurring the heavy cost of generating plant. The ultimate place of the power supply stations in relation to collieries is still uncertain.

Of the power-absorbing operations at a colliery the winding of coal is the principal in respect of magnitude, and in electric winding the Germans have given us a strong lead. Notwithstanding the advan-

tages of the system, its high cost has, in this country, impeded its adoption. Large concerns which can operate a group of pits from the same power station are in the most favourable position to avail themselves of the system. A number of equipments of high power, most of them German, are already installed or in process of erection. The restrictions which power supply companies find it necessary to impose in regard to fluctuation of demand upon their mains have checked the use of the system where otherwise it would have been adopted. Many ingenious and expensive devices have been elaborated with a view to overcoming this difficulty; later developments indicate the probable effectiveness of simpler and less costly apparatus, and a successful issue of experiments now in progress would give an impetus to electric winding, to the benefit alike of the coal owners and of the supply companies.

After winding, the pumping of water is usually the service which demands most power. In this department the turbo pump is surely ousting the reciprocating type, and here again the Germans have been the leaders. Where large volumes of water were to be dealt with, the Continental practice a few years ago was to use reciprocating pumps of the express type, driven by slow-speed motors on the crank shafts. Many ponderous machines of this type, which were generally duplicated, now stand idle in their vast underground caverns, and serve as standby to electrically driven high-speed turbo pumps.

The freedom with which costly existing plant is discarded in favour of modern appliances, is a notable feature of Continental colliery engineering. That turbo pumps will become almost universal in this country for mining work cannot be doubted; their compactness, simplicity, and satisfactory efficiency ensure for them the premier place. Many of our manufacturing engineers are alive to the necessity of developing this branch of work, and it is to be hoped that they will soon outstrip foreign competitors.

The use of compressed air for power distribution will always remain a necessity at the large number of collieries where the working of gaseous seams prevents the inby use of electricity. At such collieries the power absorbed in compressing air is a considerable portion of the total power developed.

During the past seven or eight years experimental work has been in progress both in France and in Germany in connection with turbo air compressors, and the result is seen to-day in the orders captured by our rivals for immense plants of this type, in which the individual units approach 20,000 H.P. The practice in this country is still to install cumbersome reciprocating engines, often in units of 2,000 to 3,000 H.P. Now that the turbo air compressor is an established fact it is time for our engineers to take it up. A rich harvest awaits the successful pioneer. In default of a move being made we shall shortly see modern turbo compressing plant of foreign origin ousting the obsolete reciprocating machines, and again we shall have to start a long stern chase to recover lost business. In passing

it may be noted that for driving turbo compressors electric motors as well as steam turbines will find a place.

In the driving of underground haulages main and auxiliary, the electric motor has gone far in displacing other methods. Electrical engineers in this country are much to blame for not more strongly urging the use of slower speed motors for this service, and for driving reciprocating pumps. For smoothness of working, reliability, and enduringly satisfactory results, the essentials are ample reserve of power, and moderate or slow speeds. Not only is the high-speed motor, especially of the continuous-current type, more liable to give trouble, but the tendency is increased by the vibration attending the additional gearing, and by the higher ratio of speed reduction at each step.

For operating auxiliary haulages a wide field is open to the electric motor. There is still far too much manual haulage in our mines. This is the most expensive kind of haulage. It is not work for men, and it should be reduced to the minimum. In the replacing of horse haulage also there is considerable scope. Much attention has been given to this branch, and motor-driven haulage gears of compact design are available for every variety of service.

In underground haulage, practice on the Continent has been developed along lines different from ours, and similar to the American system. There, except on inclines, a haulage rope is rarely seen. The use of locomotives is almost universal; they are operated by gasoline, benzine, or compressed air, and in open lamp pits sometimes by electricity from trolley wires. While the locomotive certainly has advantages in the assembling of trains, there can be little doubt that the rope haulage system as used in this country is the more economical. The difference in practice is interesting, and it is not accounted for by difference in the mining conditions, but rather by the personal predilections of the officials.

For drilling or otherwise removing material too hard to yield to a tool with a cutting edge, the percussive machine has no rival. The endeavour to provide an electric percussive tool with sufficient force and sharpness of impact having failed, resort has been had to electrically driven inby air compressors for operating pneumatic tools. This arrangement is now widely used, and in the service the electric motor has incidentally demonstrated the high cost in power of these tools. In some recent forms of electric pneumatic percussive machines, substantial gain in efficiency has resulted from the adoption of a closed pneumatic circuit for individual machines. This system might with advantage be extended to groups of machines operating in close proximity, as in pit sinking, and in the larger tunnellings near shaft bottoms.

Attempts have also been made to utilise inby compressors for operating Longwall coal-cutters, but these, with one or two qualified exceptions, have failed, owing to misunderstanding of the problem, which is entirely different from that of percussive machines. The percussive type requires from 50 cub. ft. to 100 cub. ft. of free air per

minute compressed to a pressure sufficient to give sharpness of impact. On the Continent, where tools of this type are much more extensively used than in this country, the tendency is towards higher pressure, and 110 to 120 lbs. in the later plants is not unusual. The percussive tool is essentially intermittent in its demand for air; it is rarely consecutively at work for more than a few minutes, and an air receiver is therefore valuable in increasing the number of tools which may be operated from a compressor of given size.

The conditions in respect of Longwall coal-cutters are essentially different. These machines require, not a small volume of air at high, but a large volume of air at relatively low pressure. As the demand for air amounts to 400 to 700 cub. ft. of free air per minute per machine, and as the machines frequently operate continuously for periods of 30 to 60 minutes, it is obvious that receivers as air reservoirs are useless. A closed air circuit for Longwall coal-cutters is impracticable owing to the size of flexible hose which would be required for the exhaust. The highest attainable economy of the system would be realised :—

1. By keeping the pressure within the practicable limit of adiabatic compression—35 to 40 lbs., and thus avoiding loss of heat by water jacketing and the resulting reduction of volume of compressed air.
2. By covering the piping with heat-insulating material, and delivering air to the coal-cutter at a temperature of over 200° F.
3. By the use of cylinders in the coal-cutters of sufficient size to develop the required power with an earlier cut-off; expansive use of air in the cylinders without freezing of the exhaust being rendered possible by the supply of warm air to the coal-cutter.

The combined effect of the economies so realised is to reduce the size of the electric motor required by about 40 per cent. Even after this is done, the capital cost is so high that the arrangement can only find a very limited sphere of application.

Recent prosecutions for alleged infringement of the Special Rules for the Use of Electricity in Mines, although involving considerable individual hardship, have also had a salutary effect in impressing upon colliery officials their responsibilities in respect of the quality and good care of the electrical equipment under their charge. The result is apparent in anxiety of those concerned to secure the best, instead of as formerly the cheapest, equipment. Now that there is a general demand for the best that can be produced, there is the strongest inducement to manufacturers to incorporate in their designs the results of recent experience and suggestion. Too much of the plant and accessories used for underground work has been produced without adequate knowledge of the conditions of service, and more intimate

understanding between users, installers, and makers is essential to the close adaptation of the appliances to their purposes.

The evidence submitted this year to the Departmental Committee by witnesses representing colliery owners, colliery managers, manufacturers and contractors will, when published, be found to contain the most competent, authoritative, and valuable body of opinion yet collected. The report of the committee and the proposed modification of the existing Home Office Rules are awaited with much interest. There still remain, however, several matters of prime importance and general interest, on which satisfactory evidence was not produced, because it does not exist. We do not know, for example, whether the motors now being made and used as "flame-proof" are to be relied upon for this quality, and the same may be said of switch-gear. A few manufacturers have made tests of their apparatus, and may be in a position to say that under certain conditions flame will not be communicated from the interiors; but the extent of our knowledge of the subject is quite unsatisfactory. A series of tests concerned with elementary stages of the problem were conducted by Mr. W. E. Earforth at Altoft's Colliery in 1903. Since then an association of German manufacturers organised a series of experiments which carried information on the subject considerably further, but still leave many important points to be elucidated. The results of these German tests were not available to English readers until two years later, when they were embodied in a paper presented to this section by Mr. Simon. There is urgent need for a thorough experimental investigation into the whole subject of enclosure of motors and accessory apparatus, in order that the conditions essential to safety may be ascertained and authoritatively stated. Until such research has been carried out with adequate apparatus, by a competent staff, we shall be without a sure basis for design.

An experimental gallery suitable for such tests exists at Woolwich Arsenal, but it seems unlikely that the Home Office will take the initiative in the matter. Another gallery, on a larger scale, provided by an Association of Colliery Owners, is erected at Altofts Colliery in Yorkshire. This gallery has a very complete equipment of apparatus, and a now trained staff is conducting an exhaustive series of experiments into the problems of the origin and propagation of coal-dust explosions. On completion of the present experiments, might not this gallery and the experienced staff, with such addition as the special nature of the enquiry requires, be utilised for the determination of the conditions of safety requisite in electrical apparatus for use in situations where gas or explosive dust may accumulate? The expense of the experiments, if shared by colliery owners and electrical manufacturers, would not be a heavy tax on any one, and it would not be difficult to find a committee which would give the stamp of authority to the published results.

Probably no branch of electrical work has been the subject of so much discussion during the last eighteen months as the use of electricity in mines. A deluge of articles has appeared in the technical

journals, papers have been read in the institutions, and torrents of controversy have been let loose. When the somewhat turbid flood is filtered, much useful information emerges, especially that contributed by those experienced in the operation of colliery plants; on this source manufacturers must to a large extent rely for guidance in design of accessories. The educative influence on colliery managers of the controversy has been most useful.

Fortunately for Scotland, the majority of the mines are relatively safe from the appalling dangers associated with gas and dust, and it is therefore possible for us to utilise electricity underground with a freedom which is denied to some other districts. Under the conditions obtaining in most of our collieries, it is neither necessary nor desirable that the use of electricity should be subjected to the same requirements and restrictions which may be reasonably applied under other circumstances. It is also to be remembered that many of our collieries are small and cannot support a staff with the same qualifications as may be expected at a large colliery; the electric equipment should therefore be of the simplest possible kind, and delicate automatic apparatus should so far as possible be avoided.

Time does not permit more than a passing reference to the distribution of power by compressed air. In view of the very extensive and permanent place in mining in this country of the compressed air system, and the large size of many of the existing plants, the general neglect of the conditions essential to an even moderate degree of efficiency is surprising.

There is good ground for the statement that the realised efficiency of the system seldom exceeds 25 per cent.; it is often much less. Many users of compressed air in mines may question this, but they do not know how badly they are doing. They are at a disadvantage as compared with users of electricity in not having available instruments of precision for the measurement of rate of flow, but air pressure is easily measured, yet the simple and easily applied pressure gauge is rarely seen underground. So long as pumps continue to pump, and haulage gears to haul, no questions are asked as to efficiency. When special occasion arises to introduce a pressure gauge—that is, when some machine refuses duty—the pressure is frequently ascertained to be less than half of that maintained on the surface. Even when the arrangements on the surface, and in the shaft and main roadways, are well designed and executed, they are rarely so continued, into what may be termed the area of movement in the mine. These are not loose statements, but are based on wide acquaintance with compressed air plants in English and Welsh collieries.

Whether low air pressure, with smaller losses in compression and larger losses in pipings, is better for colliery work than high air pressure involving greater losses in compression and less loss in transmission, is too large a subject to be dealt with here. Continental practice is in favour of the latter method, and it is probable that under the conditions of service the efficiency realised is the more satisfactory,

even when a considerable proportion of the air is used for driving machines which do not inherently require high pressure.

The foregoing considerations have had almost exclusive reference to surface equipment, and to the general power service of the mine. Without prejudice to the importance of efficiency and economy in these departments, it may be pointed out that they are merely secondary and accessory to the primary operation of winning the coal *in situ*. That so much attention and capital have been devoted to the surface and general equipment of modern collieries, while so little relatively have been expended upon direct attack on the coal by mechanical appliances, is the more surprising in view of the immense interests concerned, and of the arduous character of the manual operation of hewing. It is singular that coal-mining—one of the most ancient and important of our industries—should be the last to avail itself of the aid of machinery in its primary process. It is still not unusual for collieries to be sunk and equipped at cost of six figures, without serious consideration of machine mining. Acute difficulty of obtaining sufficient output, especially during the earlier stages of developing the workings, often forces the introduction of machines upon formerly indifferent or reluctant officials. When new collieries are sunk by companies already experienced in machine mining the course is very different; a well-considered scheme of machine mining is an integral part of the general policy, and it comes into operation directly the shaft pillar is pierced.

Attention to reduction of fuel consumption at existing collieries is well bestowed, but the importance of effecting such economy depends upon the value of the fuel used. In Scotland the average coal consumption at collieries amounts to about 7 per cent. of the total quantity, not value, of the coal raised. At an average value of 2s. 6d. per ton, the fuel used would, therefore, cost about 2d. per ton on the total coal raised. Assuming that the coal consumption could be reduced by 50 per cent., thus saving 1d. per ton on the whole output, the question remains: Could the capital expenditure required to effect this be so invested as to realise a greater saving? In many, probably in most hand-worked collieries, it could be invested to better advantage. Fuel is a small item relatively to mining costs. The cost of labour at and close to the working coal face, may be said in this district to vary between 2s. and 3s. 6d. per ton, according to thickness of seam and other conditions. The first place to attack costs is where costs are highest. In a nutshell, a 1d. per ton saved from the mining costs is, in this district, worth half the fuel bill.

How are the mining costs to be reduced? By the application of machines. In seams suitable for machine-mining coal-cutters are a first-rate investment. The possibilities and limitations of these machines are now fairly well understood, but with growing experience the former are steadily expanding and the latter are shrinking. It certainly does not state the case for coal-cutters too favourably to say that the average saving effected by them in Scotland amounts to 9d.

per ton; it often amounts to double this figure, and many seams are worked by machines which could not be worked at all by hand.

One of the most far-reaching benefits conferred upon the coal-mining industry by electricity is the facility which it affords for the application of machinery at the coal-face. The coal-cutting machine with compressed air motor was used half a century ago, but not until the advent of the electric motor did the coal-cutter secure the position to which it is entitled. The compressed air machine has been developed and improved simultaneously with the electric type.

It is satisfactory that in the manufacture and use of Longwall coal-cutters we are so far ahead of foreign competition that we are alone in the field. In Great Britain Longwall mining of coal originated, and here, therefore, machines adapted for this system have been developed.

The Longwall system for working seams of moderate thickness is finding increasing favour all over the world. To this country, foreign mining engineers come for guidance in applying the system, and from here Longwall coal-cutters are shipped to nearly every country where coal is mined.

The Germans who, excelling as surface engineers, have gone far ahead of us in many departments of colliery equipment, are not the equals of our managers as practical miners, and have everything to learn from us in Longwall machine-mining.

On the other hand, reference may be interpolated here to the admirable systems practised in Germany and Austria for working thick and inclined seams, compared with which the methods now in vogue in Staffordshire are archaic.

The introduction of the Longwall coal-cutter is the beginning of a revolution in the practice of mining in this country. The mining of the future is to be "machine-mining," and to this term a new and wide significance is to be attached. The mere application of a coal-cutter to a seam difficult or impossible to work by hand is not machine-mining. Machine-mining is a system of intensive mining, in which the whole sequence of underground operations is based upon, and co-ordinated with, the coal-cutter as the productive unit. This proposition is understood and acted upon by only some of the more experienced users of coal-cutters; unless and until it is intelligently accepted, the benefits of machine-mining cannot be fully realised.

An effect of the Longwall coal-cutter is to produce a greatly increased output from a given length of working face, and as a consequence it has introduced an entirely new problem—that of prompt removal of a relatively large quantity of coal from a small area. This necessity has brought the mechanical conveyor to the coal-face in the wake of the coal-cutter, and, in turn, the conveyor by delivery of a large quantity of coal to a single roadway has introduced another problem—the provision of a copious and uninterrupted service of trams to receive and remove the coal from the conveyor. Following

the conveyor, therefore, must come reorganisation of the auxiliary, and frequently also of the main haulage arrangements.

In an organisation so complex as a modern colliery one innovation leads inevitably to another.

No sooner is one operation accelerated than the necessity for quickening another becomes apparent. The penalty of lack of synchronism in the cycle of operations concerned in the winning of the coal, loading of it into trams, hauling of trams to the pit bottom, winding the trams to the surface, and the return of empty trams to the face, is sacrifice of the benefits of acceleration of any individual process in the cycle. The advantage of accelerating at one or more stages cannot be fully realised until the whole system is co-ordinated. The rate of flow of coal from the face to the surface is controlled by the slowest process in the series. Whenever the conditions are favourable to the use of coal-cutters, the problem is no longer the mining of the coal, but its prompt removal from the working face.

Machinery at the coal-face has increased the output per man, and has reduced the ratio of personal accidents to tons of coal produced; but, although statistics on the subject do not exist, the indications are that machinery has not affected the ratio of personal accidents to persons employed. In other words, machinery has not reduced, although it has not increased, the hazard to the individual miner. It may be here pointed out incidentally, that in respect of rescue and ambulance equipment our collieries are lamentably behind most Continental mining districts. It should, however, be stated that steps are being taken to improve our position in these matters.

Machine-mining has particular interest to Scotland, for here coal is mined under conditions much less favourable than exist in most of the mining areas of England and Wales. The thicker seams, except in Fife, have been for the greater part exhausted, and in the thin seams the problem is so to reduce the cost of working, that thin seam collieries may hold their own in the coal-selling markets.

It may be said without fear of contradiction that machine-mining as applied to thin seams is more expertly conducted in Scotland than anywhere else. The existence of many of our thin seam collieries absolutely depends upon alert, intelligent, and skilful management of machine-mining, and they would be closed to-morrow if they were in districts where extravagance and indifference were condoned by favourable mining conditions, or by high selling value of the product. Colliery managers in Scotland have especially distinguished themselves by initiative and ingenuity in devising underground conveyors. The number of different types which have originated in this district far exceeds the total number designed beyond our borders. The enterprise exhibited in this direction is an indication of the progressive tendency of mining in Scotland.

It has been shown that the developments in coal-mining call for more and more machinery.

The first requisite to the provision of plant which shall in every

detail be suitable for use in collieries, is that its designers shall be thoroughly familiar with the conditions of service which the plant and apparatus is required to endure. In colliery work there is no escape from the consequence of slovenliness in the matter of details. Weak points are inevitably discovered by usage, and in no department of electrical work are the results of carelessness more dangerous, or the benefits of thoroughness more apparent, than in colliery work.

YORKSHIRE LOCAL SECTION.

INAUGURAL ADDRESS OF THE CHAIRMAN.

T. HARDING CHURTON, Member.

ABSTRACT.

(*Address delivered November* 16, 1910.)

I thank you very much for the honour you have conferred upon me by electing me your Chairman for this session. The Yorkshire Local Section occupies, we may justly claim, a high position, on account of the importance of the work that it has done and is doing. The tree of electrical knowledge has grown apace; new branches have appeared, and, as in the case of "radio" or "wireless" telegraphy, for example, have developed with almost amazing rapidity. As a consequence, workers in the science of, and industries dependent upon, electricity are obliged to specialise more and more closely. It is by means of such a society as this that one may be enabled to contribute from one's special knowledge to the common stock of science, as well as to keep up to date in one's own particular subject, and to maintain a bowing acquaintance with many others that fall within its purview.

A recent instance of important "missionary" work undertaken by the Institution is that a Committee has been formed for the purpose of obtaining particulars respecting the operation of textile factories by electric motors, with a view to proving the advantages to be gained by the adoption of electric driving. It is to be hoped that this work will be energetically pursued and developed.

Speaking generally, we are not, I believe, so enterprising in advertising our productions or commodities as are some other nations—especially the Americans and Germans—and while I do not suggest the indiscriminate adoption of their methods or styles, I think that we might with advantage emulate their business enterprise, and, in suitable manner, make more widely and fully known the value of that which we have to offer than is customary in this country at present.

In this Local Section we might well demonstrate, by the introduction of suitable papers, the advantages of electricity as applied to the iron and steel, engineering, mining, textile and clothing, leather, and other industries that are largely carried on in our midst, and by inviting representatives of those industries to take part in our discussions upon

papers relating to the particular industry in which they are severally engaged, we shall be doing something towards educating the public in the uses of electricity to their advantage as well as to our own.

Another direction in which the interests of the electrical industry may be perhaps more completely watched is by the influence that the Institution may bring to bear upon legislation and Government regulations concerning it—pressing for the removal or revision of unnecessary restrictions and rules, and for the concession of reasonable facilities necessary for the development of electricity for the public good. The machinery exists in the Parliamentary Committee of the Council of this Institution, and I think that much more may be done by this and other Local Sections, which include men thoroughly experienced and well versed in these matters, bringing forward their opinions and the facts before the Committee, and thus strengthening the Committee's hands in dealing with such subjects. The views of an Institution such as ours, numbering well over six thousand members, must needs carry very considerable weight, and it is time that we were up and doing and minding more energetically the great interests that we represent.

Manufacture.

It is, I suppose, well known to most of us that during the past few years the electrical manufacturing business has, speaking generally, not been in a flourishing condition. In the keen competition to obtain orders, prices have been reduced and reduced, and profits have become more and more microscopic in their proportions. And yet the business has been rapidly growing, the demand for electrical apparatus has continually increased. To what, then, is this unsatisfactory state, commercially, to be attributed? It is, I believe, mainly due to the productive capacity of our factories exceeding the demand of the market that is open to us. That is, however, a matter which would probably settle itself in time, and prices might then be expected to realise a reasonable profit. But the foreigner would then be tempted to compete, and thus prevent any material improvement. So that, while prices are now, I believe, kept low by what I may call internal competition, any material increase would apparently—under existing fiscal conditions—be prevented by external competition.

It is not my intention to argue the fiscal question, but whatever views one may entertain upon that, it is, I suppose, an incontrovertible proposition that a manufacturer whose market is more restricted, is—other things being equal—at a disadvantage as compared with one whose market is less restricted. And the German or American manufacturer, therefore, for example, having the monoply of their respective home markets, and equal terms with ourselves in our own, has a decided advantage in that respect over us. The preference that we have in certain colonies, welcome as that is, is quite inadequate to compensate for such unfavourable terms elsewhere. The result is that in this unequal contest with our foreign rivals we have to work harder

and better in order to keep pace. Well, so far as the severity of competition has operated as a stimulus to increased effort in the direction of improvement and to economy with efficiency in design and manufacture, that is all very well. But so long as the same causes continue to operate, our task appears likely to remain an uphill one.

In the manufacture of electrical machinery there has been a general lowering of the cost of production. The use of interpoles and increased ventilation have enabled the weight of direct-current generators and motors to be considerably reduced. The size and weight of alternating-current motors, too, and of transformers, have been much reduced by the employment, for the laminæ, of a special steel alloy, due to Sir Robert Hadfield, and by their being well ventilated. One effect of this reduction in the size of motors is that, being more dependent upon ventilation to carry off the heat generated, when they are totally enclosed the reduction in capacity on account of heating is more pronounced. This observation applies only where the temperature rise is dependent upon the rate of radiation of heat from the exterior of the frame under normal conditions, and does not, of course, apply in the case of enclosed machines that are cooled by pipe ventilation or other extraneous means. It is not, however, always possible or convenient to adopt such measures for cooling motors, and it is certain that in many instances motors might be run more efficiently and economically at a much higher temperature than is at present considered advisable were it not for the combustible nature of the insulating materials—chiefly, of course, of the cotton covering of the windings.

The subject of insulating materials affords ample opportunity for research—we want something that will stand higher temperatures without risk of burn-out and that will last well.

No cause has contributed more, perhaps, to the reduction in cost than that which has become increasingly possible as the demand for electrical machinery has grown, viz., the manufacture in quantities of stock parts, or of complete units, thus enabling both workmen and tools to be regularly engaged on the same work or class of work. Thus there has been a marked tendency among manufacturing firms to specialise in certain lines, each developing their own standards or patterns, adopting certain varieties and sizes of their own selection, and manufacturing these in quantities to stock. This system of individual standardisation has left manufacturers free to modify their standards as experience and additional knowledge have dictated. But while it is undesirable that much should yet be attempted in the direction of bringing about uniformity in constructional details of electrical machinery, there is good and sufficient reason for an endeavour to establish agreement as to the definitions of terms used and for the adoption of certain standard specifications respecting the performance of electrical machinery.

An attempt of this nature, if not altogether successful, was made by the Engineering Standards Committee in their published Report on

Standards for Electrical Machinery. With regard to the rating of motors, it is proposed that the rating of a motor for continuous work shall be based upon its performance for 6 hours. Why? A small motor may attain maximum temperature rise in 1, 2, 3, or 4 hours, while a larger machine may continue to get hotter for several hours longer, and though not too hot in 6 hours, might become too hot for safe working when run "continuously"—perhaps driving a pump or other such steady load. Would it not be much better to specify the ultimate temperature rise attained, irrespective of the time taken for the limit to be reached? And then, again, with regard to intermittent rating, this, it was proposed, should be based upon the performance for 1 hour continuously. The fallacy of such a system of rating has been frequently exposed, by none, perhaps, more forcibly than by Dr. Pohl in an able paper * read before this Section, and I need not, therefore, now enlarge upon it.

Then, with regard to the proposed standards for B.H.P. and speed of motors, these will, I fear, be of but little practical value. One speed only is suggested for each different horse-power. But as practical requirements necessitate very different rates of speed for each size of motor, such a proposed list can only be regarded as a suggestion as to the number of sizes of motors that should be included in a standard range. As each size is constructed to work at different speeds, and as the horse-power is not quite proportional to the speed, a number of other horse-power ratings are thereby introduced. And further, as regards alternating-current motors, the output, as well as the speed, is affected by the frequency.

The standardisation of voltage, and, in the case of alternating current, of numbers of phases and of frequencies—in order that the variety of electricity supply may be as small as possible—is, of course, greatly to be desired, and the recommendation of the Standards Committee that the standard frequency shall be 50 cycles per second, with an alternative of 25 cycles where a low frequency is specially required, will, it is to be hoped, be adopted whenever a new scheme is started or an old one changed over.

Technical Training.

The tendency in electrical manufacturing is to simplify the work of the workman, and to depend less upon his knowledge and skill, excepting such as may be acquired by the continual practice of one particular kind of work. Of the managers, designers, administration, and supervising staff, on the other hand, more skill and knowledge, greater ability, and concentration of effort are continually demanded.

Now, with regard to the young workman, whichever one of the numerous "trades" he either elects, or circumstances lead him, to follow, there can be no doubt that the best, and, in fact, practically the only way to learn the work is by actual work in the shops. Will

* *Journal of the Institution of Electrical Engineers*, vol. 45, p. 216, 1910.

he be enabled to perform his work better or be able to "improve his position"—that is, to perform some work that demands greater knowledge and skill—by attending classes? That depends, firstly, upon the particular kind of work in question; secondly, upon the character and ability of the student; thirdly, upon the character of the training he receives; and fourthly, with regard to his prospect of advancement—that must depend also upon the demand for the application of the additional skill or knowledge acquired.

With regard to (1) the particular kind of work: while it is obviously impossible to generalise, on account of the variety of work under consideration, it is safe to say that in the performance of many of the operations, little or no knowledge beyond that which is gained from practice in the shop is likely to be of much practical assistance. With regard to the second point, to make a good foreman, not only is a thorough knowledge of the work necessary, but a combination of qualities that we call personality. Energy, tactfulness, method, ability to control men and get the best work out of them in some indefinable kind of way, are some of the attributes of a successful foreman. But if such qualities as these cannot be acquired by attending classes, the scientific principles can be learnt, and the course of his studies be guided at the technical classes. Special care should be taken to ensure that the training is appropriate to the work in view, and that it is not "over the heads" of the students. At the same time, it should be borne in mind that excessive specialisation tends to make a man a mere machine, and that he is then apt to suffer the fate which not uncommonly overtakes machinery, viz., to be superseded and "scrapped," and thus find himself among the unfortunate unemployed and unemployable. It therefore behoves every workman to know something more than is necessary to do just the work that he may, for the time being, be engaged upon, so that he may be able more readily to adapt himself to such changes and developments as may take place. The Education Department in this city appointed an Advisory Committee consisting of manufacturers engaged in various industries, and others, with the object of conferring with the managers of the technical schools as to the courses of study and other cognate matters, and such co-operation must be mutually beneficial.

Now, with regard to the training of men with a view to their becoming designers or managers. Although specialised, the training should be much broader than that which is appropriate to the workman. The success of the designer does not depend only upon his knowledge of theory and science, nor upon his skill in mathematics, but upon his power of observation and of the grasping of problems; upon his ability to combine ideas and to form new ones, such as originate improvements, inventions, new applications or adaptations.

It cannot be too clearly impressed upon the student who would become an electrical engineer that neither the works course nor the college course can independently fit him for any superior position, but that both courses are equally essential.

May I add that whatever may be the training, the British workman still maintains his position of superiority among the nations of the world. Having visited works on the Continent and in America, I have realised this fact particularly, that when any difficulty arises, the English workman is better able to cope with it than that of any other nation that I have had the opportunity of observing.

Electrical Distribution and Coal Conservation.

Gentlemen, it may be expected of your chairman that he should endeavour to point to the lines of development of the future. I will do my best to indicate in at least one direction the course that progress may be expected to take, especially as it is, I am confident, one of national importance. I refer to the development of the electrical distribution of power as a means of conserving one of our most valuable, and indeed vital, natural resources—coal.

The sources of energy or power, for which we are indebted almost wholly to the sun, may be divided into two classes: (1) That in which energy has been deposited or stored up in the earth through chemical action in past phases of the earth's history, and which is now being reproduced; and (2) that which is due to the present action or activity of the sun's rays and is thus continuous.

In the former class we have coal (in its various stages from peat and lignite to anthracite), petroleum, and natural gas; and in the latter are chiefly vegetable growth (timber), that which is derived from falling water in rivers or tides, and that which is due to the motion of the atmosphere—or wind. Wind is not usually a convenient source of power; a power that is more under control is preferred. Water-power—of immense importance in some countries in which there are falls capable of developing continuously vast amounts of available energy—is, comparatively, but little in evidence in this country. As regards the use of timber as fuel for the development of power, I may say that in the United States, according to the Forestry Department, the amount of timber used for fuel alone is nearly equal to the amount grown each year, and that without taking into account the tremendous loss due to forest fires, timber is being taken from the forests at the rate of about three and a half times their yearly growth. At the present rate of depletion, the total annihilation of the vast American forests is well within sight. The growth of sufficient timber for use as fuel for the power required in this country would certainly not be practicable.

We cannot, then, look to any of the perpetual sources of power to fulfil the requirements of our national economy as a manufacturing nation, and must therefore depend upon that which has been stored up in the surface of the earth millions of years ago, and which, so far as this country is concerned, is limited to the coal measures. Now, though it has been estimated that the coal existing in the United Kingdom is about 140,000 millions of tons, which represents, roughly, about five hundred years' supply at the present rate, it must be remembered that

as the better and thicker seams, and those nearer the surface become worked out, the cost of getting the remaining thinner and deeper seams becomes greater, and that for various reasons enormous quantities will probably never be won at all. To realise the force of this, one has only to consider that in comparatively recent times coal was chiefly got in "day-holes" at the outcrop, or from shallow pits but a few yards in depth, while now shafts are being sunk to seams at a depth of a thousand yards or more. And thin seams that were left formerly as not being worth working, are, as the thicker seams are exhausted, being worked, usually at a greater cost. Recognising, then, that our supply of power depends upon coal, and that coal must become more expensive (and finally give out), the necessity for economising it must become increasingly important. For this reason, we may look forward, I think, to the more general adoption of electrical distribution of power from generating stations with plant-units of much larger capacity than we have at present, linked up with collieries, steel works, and other places at which enormous quantities of heat energy are continually being wasted, but which by means of subsidiary generating stations may be turned to useful account. Without entering into the relative advantages of gas and steam plants, I may point out that as fuel becomes dearer, the greater thermo-dynamic efficiency of the gas plant must tell more strongly in its favour, while its greater capital cost will become of relatively less importance. Should the gas engine be not so developed as to render it suitable for the large power-station set, it may prove efficient in the subsidiary power houses. The advantage of large size in steam sets is seen not only in increased economy in steam consumption, but also in other operating costs—attendance, oil, etc.—and in building space, and I think, therefore, that we may confidently anticipate the adoption of much larger units than we have at present. Here in Leeds the largest sets are of 3,000-k.w. capacity; in Sheffield, the largest is 4,000 k.w.; at Manchester, the largest set, I believe, in operation in this country, has a capacity of 6,000 k.w. At the Delray Station of the Detroit Edison Company (Michigan, U.S.A.), which I recently visited, there are several sets of 14,000-k.w. capacity. These are of the Curtis vertical turbine type with generators made by the General Electric Company, of Schenectady, N.Y., and running at 720 revs. per minute, deliver 3-phase current at 60 cycles, 4,600 volts. The steam pressure is 180 lbs., and the consumption is, I believe, about 14 lbs. per kilowatt-hour. So smoothly do these sets run that, standing on the top of one of them while turning round 12,000 k.w., I noticed scarcely any vibration. The height of these sets is 37 ft., the turbine blade-rings are 13 ft. in diameter, and the revolving field 9 ft. diameter. The boilers are of the water-tube type, and one of the large ones will keep 8,000 k.w. going. The day-load of this station is, I may add, about 22,000 k.w., which includes street-car service. As indicating the success of this station, I may mention that arrangements were being made, so I was informed, to replace two of the smaller sets by two more of 14,000 k.w. each.

The smallness of the power house and the fewness of the attendants —relatively to the output—struck one as remarkable, and was to be accounted for, of course, by the generators being few in number but of great capacity.

Now, the economical generation of power that may be thus secured, coupled with cheap and efficient distribution by means of high-tension overhead wires, enables the power company to sell and deliver power at a cheaper rate than the consumer can generate it with relatively small plant, and a ready sale for the energy is thus assured. To enable a power station to generate at a lower cost than the private user, it must, in fact, be equipped with more efficient plant, be run at a less cost per unit in attendance and other standing charges (including interest on a lower capital outlay per unit) than is possible to the user; and the difference must be sufficient to cover the cost of distribution and leave a margin of profit for the power company. It must be obvious, then, that if the power company would have the large consumers as customers (especially those whose load factor is high—such, for example, as textile mills), they (the power company) must adopt plant and economies that are quite beyond the reach of such consumers. The more that the plant and working conditions of the two assimilate to each other, the less must be the chance of the power company being able to offer any advantage. Higher voltages of transmission will be necessary to reduce as much as possible the cost of distribution, and this presents no difficulty. In America and on the Continent very much higher voltages are in use than we have in this country—30,000, 40,000, 60,000 volts being common, and in some cases voltages of 100,000 and 110,000 are in perfectly satisfactory operation. And though, in our climate, voltages of the order of 100,000 on overhead lines might render insulation difficult, and loss from corona effect serious, and though for the greatest distances with which we shall probably have to deal, voltages of such magnitude will not be necessary, yet I venture to think that voltages of 40,000 or 50,000 will be quite practicable, and will probably be adopted in our long-distance transmission and distribution schemes in the near future. In this neighbourhood we may see overhead lines of the Yorkshire Electric Power Company in which the voltage is 10,000, the conductors being only 18 in. apart, supported on double-shed insulators of 8 in. diameter. No difficulty is experienced, I am informed, with the insulation, though the atmosphere through which the lines pass certainly cannot be described as particularly free from either smoke or moisture. As the Yorkshire Electric Power Company is already transmitting to a distance of 21 miles, and as further extensions are in progress, we may suppose that as the demand upon the lines increases, the voltage—and thus the power-carrying capacity—of the lines will be raised.

Looking for a moment at the consumer's end, he has the efficient metal filament lamp for lighting; motors for the driving of his machinery, the efficiency of which leaves but little room for improve-

ment; convenient appliances for domestic purposes—all waiting for the supply of cheap power to multiply their use an hundredfold. The public are, I believe, becoming sensible of the advantages that the uses of electricity afford, and a bold policy of progress in electric power supply will, I feel sure, meet with its due reward.

In this connection, and with regard to those electricity supply undertakings that are in the hands of municipalities, may I say that, much as I sympathise with the relief of rates, I think that our city fathers may be sometimes tempted to pursue a policy that may not, perhaps, be inaptly described as "penny-wise and pound-foolish." Surely it were the better policy vigorously to develop an undertaking in such a way as to enable it to turn out its product in the most efficient and economical manner, and thus to provide cheap power to a far greater number of citizens to their advantage, and to the benefit of the city as a whole.

Gentlemen, the popularisation of electricity for power, heating, lighting, and other purposes will, by such means, not merely economise the use of coal and thus conserve our national resources, but will at the same time clear our land of the pall of smoke that hangs over it, that fouls the air we breathe, kills the plants, trees, and flowers in and around our cities, blackens our buildings and houses, and depresses our spirits by hiding the brightness of the sun from our eyes. It is no idle dream, I think, to look forward to a change in all this—and that in the not far-distant future. It is surely the duty of this Institution of Electrical Engineers as a body, and of us as individual members, to do what lies in our power to promote the development of electricity in the public service and to the national advantage.

BIRMINGHAM LOCAL SECTION.

INAUGURAL ADDRESS OF THE CHAIRMAN.

M. J. RAILING, Member.

(*ABSTRACT.*)

(*Address delivered November* 16, 1910.)

I do not propose, gentlemen, to give you a technical paper to-night, but in looking round for a suitable subject for my address it struck me that since nothing can be more important for all of us than the welfare of our industries, and through them of our profession, and since I am closely connected with a large variety of the electrical industries in this country, I shall be doing my duty best if I express my thoughts and views on the present position of our electrical industries and at the same time give you certain conclusions to which I have come; conclusions which, if followed, I feel convinced, would help us to raise our efficiency and our status in the world's market.

I have referred to the welfare of electrical engineering, and I think that all of us, in whatever branch of engineering we may be, whether scientists, consultants, station engineers, or those connected with the manufacturing industry, cannot help admitting that our position is not what it ought to be.

Want of suitable and profitable employment, or absence of satisfactory returns for the labour, or capital spent, has made itself felt for a number of years. Many are the reasons brought forward to explain this state of affairs, and many have been the suggestions for remedies. It is my contention that most of us, being imbued with somewhat conservative opinions, have not fully realised the very altered conditions in this country, and have consequently not adapted ourselves to the new demands. "Tempora mutantur et nos mutamur in illis"— I should like to translate this into English: "Times change and we ought to change with them," not "we do change with them." Conditions have changed, but our industry has not kept pace with this altered situation, in all its aspects. Now let us ask ourselves for a moment, if we have failed to progress sufficiently in our profession, what then are the factors which go to produce progress in any profession in a circumscribed territory or community, and which do we lack?

I will not refer to the improvements due to intuitive genius, as this is a factor beyond our control. The other factor which influences progress in a profession such as ours, is *dura necessitas,* when existing problems cry out for solution, and of a necessity men are employed to work on them with the object of bringing about their solution. I would give as an example of my meaning, that it is natural, at a time when one tries to develop all the motive power at one's disposal, that the development of water turbines will be worked out mostly in those countries where water-power is going to waste, the development of steam engines where coal is available. In fact, in every industry daily problems of this nature present themselves to the minds of those employed, calling upon them to set to work and find a solution.

The second factor towards progress should be more prevalent in this country, with its large number of industries, than in any other part of the world, though of late years, with new countries consolidating around us, this advantage is slowly being lost. It is this second part that I want to investigate closely, and which I wish to examine under the headings: "Where we Stood," "Where we Stand," and "What can be Done to Keep us where we Stand or to Give us a Lift Up?"

"*Where we Stood.*"—The geographical position, the early political consolidation and freedom of England, and the inherent qualities of its people, have in the past helped to make England the *trading country* of the world. The old world's products were sent here to be taken out to new worlds and to bring back in exchange their products to the old countries. This, at a time when knowledge travelled slowly, made the English foremost experts in the wants of other countries, and in the products or goods they could give in exchange. It taught, further, what these products could be made into, how they could be improved by manufacturing more valuable products out of the raw material: thus necessity forced England into the position of the best buyer and the best seller, and finally brought about the commencement of manufacturing in this country on a scale never before dreamt of.

European countries, which during this time had been engaged in internal turmoil and warfare, religious and political, now started to consolidate, became bigger and more powerful units, more open for possibilities outside their borders. An era of invention started simultaneously. The development of railways and other means of communication made the factor of distance less important. The telegraph, telephone, and the great development of educational and printed matter all round, served to bring humanity much closer together, and to distribute special knowledge over vast areas. In this way our special experience of markets and of the possibilities of manufactures was distributed to other nations, and we were thus deprived in two directions of the special advantages of our geographical position.

"*Where we Stand.*"—We thus see ourselves face to face, after this

levelling-up process, with competing nations, and we have to ask ourselves, "What are the advantages left of England's former leading position?" Apart from the advantages of good-will which the man in possession always has, and apart from the great advantages which such imponderabilities as common interests, common language, and common descent give with the markets of the colonies, we shall only progress if in the world's market we can supply our manufactures better than others or cheaper than others.

There is still possibly in a number of industries, perhaps not in our own, although in others on which we depend, the advantage of a longer experience and a greater insight into the actual market conditions and into the intricacies of manufacture, but it is an advantage which must decrease from year to year.

There is in our workmen and engineers probably an asset, on account of certain hereditary qualities developed for generations; but, again, our rivals are bound in time to diminish this difference, which, besides, is made less important through the introduction of automatic machinery. It remains to ask ourselves, "Can we produce better or cheaper on account of the raw material at our disposal?"

The fundamental basis of manufacturing industries lies in the source of their power, and whilst England in this respect may count upon a plentiful coal supply, other nations, by drawing upon their natural water resources, have an even cheaper source of motive power. It cannot, therefore, be admitted that England can justly claim any advantage over some of the other manufacturing nations.

Next to the primary power, the most important factor to be taken into consideration is raw material. In our own profession, for building up our machines, we mostly are in want of iron, steel, and copper. It is a well-known fact that some forty years ago England was pre-eminent in the production of iron and steel, but this pre-eminence has gradually, but surely, faded away.

In confirmation of this statement reference may be made to the figures for the production of pig iron by the Duke of Devonshire in his recent Presidential Address to the Iron and Steel Institute.

Again, in the production of copper England at one time could rely upon her resources, but at the present time the United States of America are able to produce more than 50 per cent. of the world's output. The enormous capacity of other copper producing countries has made it practically impossible to mine that metal in this country with commercial success, and we cannot close our eyes to the fact that as regards procuring copper cheaper than other nations England does not hold a more advantageous position.

As, therefore, we can claim neither advantage in labour nor in raw material, the only way in which we can get a balance in our favour is by the more efficient organisation of our factories and the labour employed in them, by means of careful supervision of the minutest details. It is hardly necessary to an audience of engineers to lay stress on the necessity for large outputs and a constant flow of work,

Perfection of organisation is only possible with such conditions. How we may help to provide for this constant flow I will endeavour to show you.

What can be Done to Keep us where we Stand?—If we want to keep our position or "move up" we must get bigger outputs and larger markets. Other countries do not possess advantages over us in the supply of raw material or power. We possess as good scientists, designers, and engineers, and as capable, if not more capable, work-people. It is output which we want to give us the lead again, and men who can give us that output; men who know best where to obtain the most satisfactory supplies and what markets are most suited for the disposal of our products.

To-day we have on the one side our factories producing commodities—generators, motors, lamps, accessories, and, in fact, anything which can be used in the applications of electricity. On the other side, we have in our own country and in all the countries of the world industries waiting, perhaps unconsciously, for the possibilities of electricity, and that man is most needed who can bring them together. The man best fitted for this work will be the one who knows not only most about the first country, that of the manufacturer, its products, its capabilities, and the possibilities of its known treasures and slumbering resources, but also he who knows most of the second country where these products are wanted, what seed is best to put in the soil, and how it is best to be sown. And one thing more is wanted—this man must know how to navigate from one country to another, how to bridge the stubbornness of the one and the greediness of the other. For all this knowledge a man is needed who knows both countries well, their different needs and temperaments, their language and their individualities.

Therefore let us teach and raise engineers with the fullest possible knowledge, shall we call it, of the geography of the two countries, the two dominions, and able with the old spirit cheerfully to navigate from the one to the other, whether through known or unknown seas. Such men must know what we can do, whether in the production of power, plant, or motor-driving, or the different sources of electric illumination, or in transport, or the means of inter-communication, and must know why we make goods in a certain way and not in the way of our competitors.

They must know the country of our customers, and all its activities: agriculture and its wants in connection with electricity, iron and steel industries, mining, cotton, chemicals, shipbuilding; they ought to see these industries and other less important ones in the light of the soil in which they are planted, and not only at home, because the world is their field of operation.

Then let us teach him to navigate, teach him about men—their characters, their individualities, how they can be led, teach him to negotiate as of old, to make contracts, to know law, make him speak languages, and make him understand the peculiarities of other countries and other nations; teach him also to rely on his own resources and

calculations, so as to be able to bring them to bear on new problems as they arise. In this way we can translate the colonising spirit of old England into modern language, and the old trading spirit into the proper modern spirit of our profession and our industry. We shall have produced a generation of commercial engineers, or engineer traders, who will be able to give you back the old predominance, and in doing so, incidentally they will allow us to produce in larger quantities, and therefore, more cheaply, in larger quantities and therefore better.

I have endeavoured to impress upon you my conviction that other countries have stolen a march on us, not so much in the production of engineers nor yet in the production of purely commercial men, but in the development of a type of man who combines the qualities of both. Those who are familiar with the continental systems of education will know that the young electrical engineer abroad is encouraged to study, in addition to his own science, the technology of allied trades, and to train himself as well in languages, in commercial law, in natural economy, and in commercial routine generally.

I plead that such an excellent course may some day be adopted in this country as well.

I further plead that the commercial side of engineering should be considered in our present system of apprenticeship. We are giving our young engineers a good practical training by making them, in a three or five years' course in our workshops, conversant with the practical problems of engineering, both manufacturing and in its applications. I claim that it is in the interest of everybody concerned that at least a certain period of such apprenticeship should be spent in the commercial organisation, be it either in the counting-house or sales organisation.

Her geographical, agricultural, and trading explorers, her travellers and colonists of the past, have raised this country to her present position. English explorers and travellers are wanted once more to set to work on new lines and win back that volume of business that has been lost and is continuing to be lost, and thus confer upon our industries and our profession the standing which it ought to have amongst the nations of the world.

THE IRREGULARITIES IN THE ROTATING FIELD OF THE POLYPHASE INDUCTION MOTOR.

By CHARLES F. SMITH, M.Sc., Member.

(*Paper received August* 5, 1910. *Read before the* MANCHESTER LOCAL SECTION *on November* 8, 1910.)

CONTENTS.

General.—The want of uniformity in the rotating field of the polyphase induction motor is due chiefly to the following causes :—

1. Non-sinusoidal wave-form of the supply voltage.
2. Disposition of the stator winding in a limited number of slots.
3. Variation of the air-gap reluctance due to the varying position of the teeth and slots of the rotor in relation to those of the stator.
4. Want of uniformity of the air-gap due to the rotor being out of centre.
5. The effect of want of proportionality between magnetising current and flux may also be mentioned, although of less importance.

1. No attempt is made in the present paper to deal with the first of the causes enumerated above, since its origin is independent of the motor. Goldschmidt* has shown that an induction motor somewhat

* *Electrical Review*, vol. 54, pp. 571 and 611, 1904.

resembles a condenser when supplied with a distorted voltage wave, in causing harmonics in the voltage wave to appear in an exaggerated form in the wave of current. This is due to the fact that the slip of the rotor is small in relation to the flux due to the fundamental, but large in relation to fields due to the higher harmonics, which rotate at a speed which is some multiple of that of the main field. The harmonics in the wave of applied voltage thus induce voltages in the rotor which have a comparatively high value and which produce in the rotor, and consequently in the stator, currents of large amplitude.

2. The second cause of irregularity can be subjected to fairly simple mathematical treatment, and is discussed in text-books and elsewhere from this point of view. The results of such a calculation, as given by Krantz,* are summarised in Appendix C. The chief irregularities coming under this head are a periodic change in the total flux of the rotating poles, a periodic change in the speed of rotation of the field, and a difference in the values of the maximum tooth induction of the teeth of the stator situated in various positions relative to the exciting coils. It can be shown that the two last named irregularities have their greatest effect in the teeth situated between a pair of adjacent phase-windings. Thus in a 3-phase 4-pole motor with two pole-windings per phase, there will be twelve points in the stator where the variation in intensity and in speed of the rotating field will be specially great. These variations will give rise to pulsations in the rotor voltage, having a frequency which at synchronism will be six times greater than that of the supply voltage. This effect is very clearly marked in some of the oscillograph curves given later.

3. The third source of irregularity, the flux pulsations in the teeth of the core, has been studied indirectly from measurements of the losses resulting from it,† but the extent to which it modifies the rotating field and affects the voltages in the motor windings has not received so much attention.

Messrs. Simons and Vollmer‡ have given some interesting curves of rotor and stator currents with the motor at synchronism and also under load, but without showing the connection between the effects observed and the amplitude of the actual field pulsation.

4. The author thinks that want of uniformity in the air-gap of induction motors is much more general, and is responsible for more waste of power than is generally recognised. The experimental determination of the power lost from this cause does not come within the scope of this paper, but several points bearing on the matter are obtained.

* *Elektrotechnische Zeitschrift*, vol. 22, p. 274, 1901. *See also* Hellmund, *Transactions of the American Institution of Electrical Engineers*, vol. 27, pt. 2, p. 1373, 1908; and *Electrical World*, vol. 52, p. 1342, 1908.

† Bragstad and Fraenckel, *Elektrotechnische Zeitschrift*, vol. 29, p. 1074, 1908; T. F. Wall, *Electrician*, vol. 58, pp. 752 and 797, 1907; Linke, *Elektrotechnische Zeitschrift*, vol. 28, p. 964, 1907; Zipp, *Elektrotechnik und Maschinenbau*, vol. 26, pp. 443 and 977, 1908.

‡ *Elektrotechnische Zeitschrift*, vol. 29, p. 93, 1908.

Description of Method of Carrying out Experiments.—The results described in the paper are based on measurements of the electromotive forces induced in special search coils wound on the stators of two induction motors, so as to embrace portions of the air-gap flux of the motors. These search coils were disposed in various positions round the stator, and were wound so as to embrace different numbers of stator teeth.

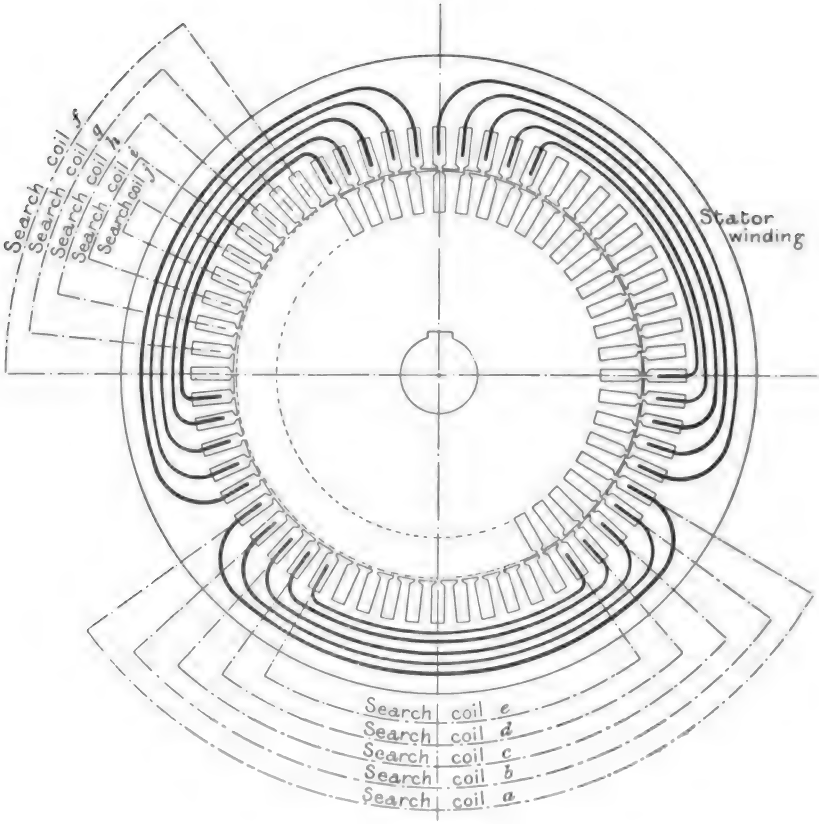


FIG. 1.—Showing Positions of Search Coils.

A 15-H.P. 4-pole 3-phase motor made by the Phœnix Dynamo Manufacturing Company, Bradford, was selected for the first series of tests. Ten search coils of fine wire were wound on the stator in the top of the slot openings, just above the actual stator winding, but inside the wooden wedges used for securing the winding. The positions of the search coils is shown in Fig. 1. It will be noticed that coils *a*, *b*, *c*, *d*, *e* embrace respectively the same number of stator teeth as the coils

which form one pole of the stator winding. The voltages induced in these search coils represented, therefore, the five coil voltages which together made up the voltage of one complete pole-winding of the stator. The remaining search coils had a smaller span, and were situated on another part of the stator. The search coils were formed of fine silk-covered wire, and were composed of ten turns in the case of the first five coils, and fifteen turns in that of the other five coils. A multiplier has been employed in the calculated results given in the paper, reducing all observations to the equivalent voltage of 15 turns.

The following are particulars of the motor windings:—

> Stator mesh-connected, 60 slots, 11 conductors per slot.
> Rotor star-connected, 48 slots, 12 conductors per slot.

The stator supply was at 50 cycles, derived from a source giving a nearly perfect sine wave. The dimensions of rotor and stator slots were alike. The shape of the slots is shown in Fig. 2.

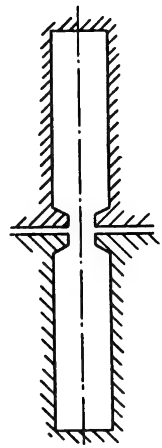


FIG. 2.
Full-size
Sketch of Slots.

Voltage Induced in Coils with Rotor Stationary.—The voltages induced in the search coils with the rotor stationary and the normal voltage applied to the stator are indicated in the form of a curve in Fig. 3, where the letters along the base are those used for identifying the several coils. The upper curve formed by joining the black dots is the one referred to.

Coil *c* shows the highest induced voltage, because its span is that exactly corresponding to one pole-pitch of the motor, and it therefore embraces the greatest flux. Coils which have a smaller span do not embrace so many lines, while those with a greater span include some lines of opposite polarity, which diminishes the resultant flux through them. The voltage of search coils *a*, *b*, *c*, *d*, *e* are linked with the same flux as the five stator coils which go to form one pole-winding of the motor. The voltages on Fig. 3 may, therefore, be taken to represent the proportion in which the applied voltage is distributed between the coils which compose the stator winding. The relative values of the voltages in the successive coils agree almost exactly with the theoretical values calculated on the assumption of a sinusoidal distribution of flux (see Appendix A). The voltages of the coils of shorter span—viz., coils *f*, *g*, *h*, *i*, *j*—are seen to form a continuation of the curve given by the first five coils, but are apparently drawn to a smaller scale. The explanation of this break in continuity is to be found in the fact that the two sets of coils were wound on different parts of the stator, where the air-gap flux had different values, on account of slight differences in the length of the air-gap caused by wear in the

bearings of the motor. The lack of uniformity in the air-gap round the circumference of the rotor, which is here made noticeable, is referred to at greater length later on. From measurements made for the author, it would appear that comparatively few motors in regular service can be said to have a uniform gap. In the present case the air-gap clearance was found to be 32 mils at the top of the

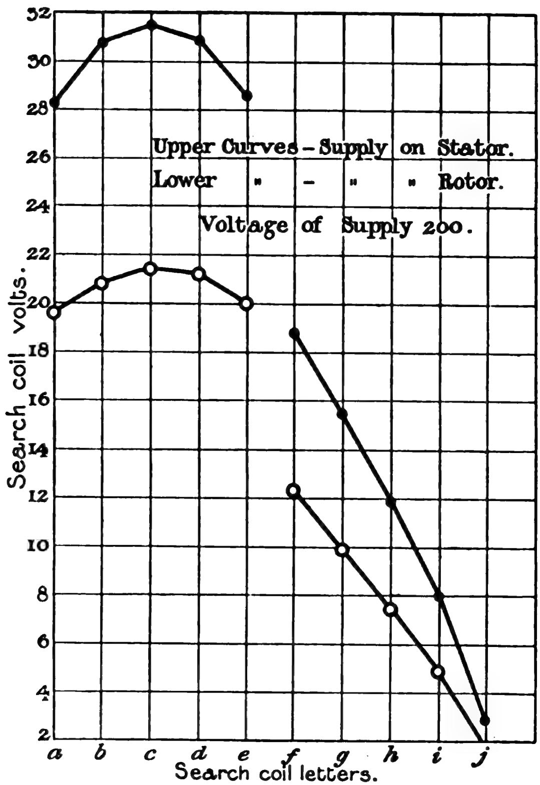


FIG. 3.—Voltage in Search Coils—Motor Stationary.

rotor and 26 mils at the bottom. In some other cases observed, the proportionate divergence from uniformity was much greater.

A 3-phase supply at 246 volts was next applied to the slip-rings of the stationary rotor and the search-coil voltages observed. These readings reduced in the ratio $\frac{200}{246}$, so as to represent an applied voltage of 200, are shown by the lower curves on Fig. 3. These voltages are related to one another in the same way as those shown by the upper curves.

On dividing the ordinates of the upper curve by those of the lower one, we should expect to obtain a figure equal to the ratio of rotor to stator turns (except for the small magnetic dispersion occurring at no load). The mean quotient obtained in this way from the coils *a*, *b*, *c*, *d*, and *e* is 1·44; while the mean for coils *f*, *g*, *h*, *i*, and *j* is 1·62. The actual ratio of rotor to stator turns is 1·51, which agrees very nearly with the mean of the two ratios just found. The discrepancy between the two ratios obtained from the search coils is due to the circumstance that the readings forming the lower curve were taken with a smaller value of the air-gap induction than normal. It is shown more fully later that, when the air-gap of the motor is not uniform, there is a different distribution of the flux round the stator for each value of the applied voltage, brought about by the unequal saturation of the teeth at different parts of the air-gap. Coils *a* to *e* were situated near the bottom of the motor, where the air-gap was small; the teeth at this point were consequently highly saturated, and these coils absorbed a proportion of the applied voltage which became smaller as the induction was raised. Exactly the reverse was true of the coils *f* to *j*. The higher ratio of the coil voltages of the second group of coils is thus accounted for. The matter would not have been worth calling attention to except as showing that considerable errors may easily be made in the determination of the dispersion coefficient of a motor from experimental readings made at voltages other than the normal. It is worth pointing out that the same effect may produce an out-of-balance voltage in the rotor, and so alter the apparent ratio of transformation as measured on open circuit, unless the volts are measured on all three phases.

Grouping of Coils.—On connecting the search coils belonging to one pole together in series, the resulting voltage was found to be equal to the arithmetic sum of the voltages of the individual coils. This was to be expected.

The group of coils *a* to *e* embrace the same flux as one pole winding of the stator, being wound in the same slots. The voltage generated in this group with a stator applied voltage of 200 was 155. Since the coils had 15 wires per slot and the stator 11, the voltage in the stator pole-winding was approximately $155 \times \frac{11}{15} = 118{\cdot}5$ volts, leaving only 81·5 volts for the other pole-winding situated opposite to a larger air-gap. This calculation is not quite correct, since the 11 stator conductors per slot do not form eleven complete turns; but it shows a considerable inequality in the distribution of the applied voltage between the coils of the phase-winding.

Effect of Rotation on Stator Flux.—As soon as the rotor is short-circuited and allowed to rotate, the values of the search-coil voltages observed with the supply on the stator, change to those shown by black dots in Fig. 4. The curve is slightly different in shape from the one taken with the rotor at rest (see Fig. 3) owing to the addition of higher harmonics of voltage, which vary in amplitude for the several coils. The nature of these harmonics, which are introduced by

flux pulsations in the teeth, is studied in connection with the later curves. The effects of load on the motor and of driving the motor by means of a separate machine with open-circuited rotor were also tried. No alteration in the induced voltages was to be observed, except for a very slight change caused by the variation in the harmonics, which depend upon the speed of the motor. The coil

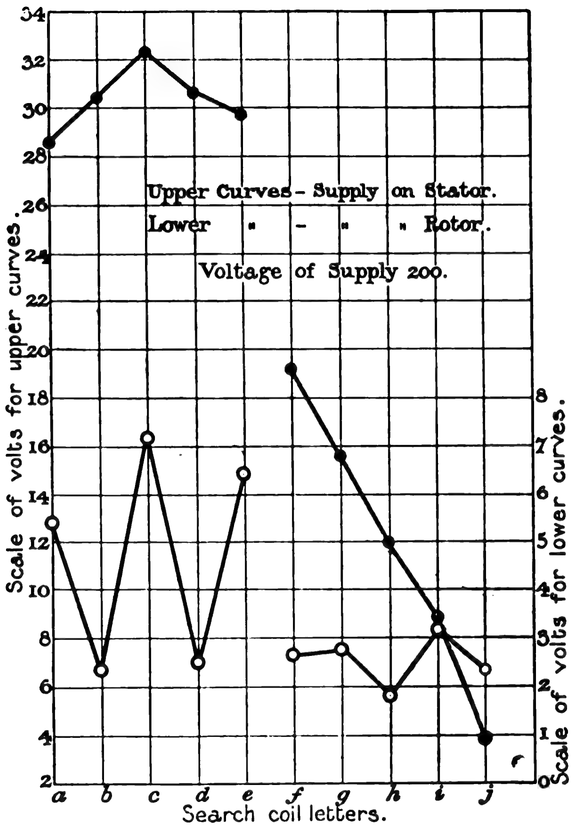


FIG. 4.—Voltage in Search Coils—Motor Rotating.

voltages were also found to be unaffected by a reversal of the direction of rotation of the rotor.

Effect of Rotation on Rotor Flux.—By connecting the rotor slip-rings to the supply and short-circuiting the stator winding, the functions of the two motor windings are inverted, and the search-coils may then be used for studying the voltages which would have been induced in them if they had been situated on the rotor, instead of on the stator, of an induction motor. We can therefore employ them to examine the

voltages induced in a rotor under working conditions. The lower curves in Fig. 4 show the search-coil voltages induced with the rotor supplied in this way and of a load of about 5 H.P. on the motor. The voltages are, of course, lower than when the rotor was stationary, but are seen to be much higher than would be produced by a uniformly rotating field cut with the speed of slip. Thus the voltage of coil *c* with stationary rotor was 21·5 (see Fig. 3), so that with the measured slip of 2¼ per cent., the voltage of this coil would have been only about half a volt in a uniformly rotating field, instead of more than 7 volts.

Another striking peculiarity of the curves in Fig. 4 is the great difference between the voltages induced in successive coils, which gives them a "saw-tooth" appearance. The two characteristics of the rotor flux indicated by these results are due to :—

1. Want of uniformity of the main rotating field due to the disposition of the stator winding in a limited number of slots.
2. Pulsations produced by the rotation of the teeth of the rotor core.

The greater part of the amplitude of the voltages shown in Fig. 4 and nearly all the "saw-tooth" effect can be shown to be due to the second of these causes.

Curves which were in all essentials similar to those in Fig. 4 were taken with other values of the motor load, and also with the stator winding open-circuited, and a second motor employed for driving the rotor. In order to separate the voltages due to field irregularity from those due to the slip of the motor, the rotor was coupled to a synchronous motor and driven at synchronous speed. The readings taken on the coils under these conditions, and representing the voltages of the rotor of a synchronously running induction motor, are given in Fig. 5. The voltages here shown may be said to be entirely due to irregularities of the field. The amplitude of the voltages in Fig. 5 are less than their true value at the normal voltage in the ratio of 233/300, which is the ratio of the voltage actually applied to the slip-rings to that giving the normal working field.

In driving the motor synchronously, we are introducing conditions unlike those of the previous set of experiments. The main field is now stationary with regard to the coils, and the value of the voltages induced in them will depend on the position which the field happens to have taken up with regard to them. This was very clearly shown by driving the motor at a speed slightly below synchronism, and observing the fluctuations in the voltmeter readings, which oscillated between maximum values agreeing fairly closely with those given in Fig. 5 and values which were much lower, but which never reached zero. The conditions under which the readings of Fig. 5 were taken were such as to make the voltage of coil *c* a maximum, that is to say, the conductors of this coil must have been situated at points of maximum flux.

Value of Flux Pulsation.—What is generally understood by the flux pulsation in a tooth is the variation in the strength of the flux passing through it on account of the varying reluctance of the air-path interposed between the tooth and the core opposite to it, as the rotor teeth revolve. There is another sort of pulsation possible, due to the rotation of the main field past the points of varying reluctance represented by the teeth and slots. This form of pulsation is practically the same as occurs in the armatures of alternators, which has been investigated by Messrs. Worrall and Wall.* With a synchronously driven motor we are concerned only with the first kind of pulsation. We may obtain an idea of the ratio of the pulsation flux to the total flux per tooth from the values of the voltages induced in coil *j*, which consisted of fifteen turns wound round a single tooth of the stator. With stationary rotor and

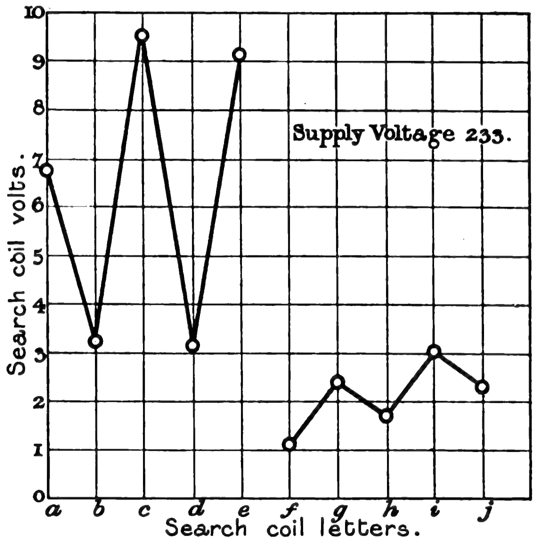


Fig 5.—Search Coil Voltages in Rotor of Synchronously Running Motor.

normal voltage applied to the stator, the voltage induced in this coil was 2·8 at 50 cycles (see Fig. 3) corresponding to a flux in the tooth of—

$$F = \frac{2 \cdot 8 \times 10^8}{4 \cdot 44 \times 15 \times 50} = 84{,}200 \text{ C.G.S. lines.}$$

The voltage induced in the same coil with the rotor supplied and driven synchronously consisted almost entirely of a series of nearly equal waves, having a frequency twenty-four times as great, due to the

* Worrall and Wall, *Journal of the Institution of Electrical Engineers*, vol. 37, p. 148, 1906; see also Worrall, *ibid.*, vol. 39, p. 206, 1907, and Wall, *ibid.*, vol. 40, p. 550, 1908.

forty-eight teeth of the rotor (see Fig. 15). This voltage is seen from Fig. 5 to have a virtual value of 2·3 volts. Making, as before, the assumption of a sinusoidal variation, the pulsating flux will be given by—

$$F'_p = \frac{2{\cdot}3 \times 10^8}{4{\cdot}44 \times 15 \times 50 \times 24} = 2{,}880 \text{ C.G.S. lines,}$$

or at the normal working voltage we should find the pulsating flux equal to—

$$F_p = \frac{300}{233} F'_p = 3{,}720 \text{ lines,}$$

forming $\frac{3720}{84200} = 4{\cdot}4$ per cent. of the total flux of the tooth.

Effect of Flux Pulsation on Coil Voltages.—A little consideration will make clear the reason for the "saw-tooth" character of the curves of rotor voltage. When the coils are of sufficient span to embrace a considerable number of teeth, the pulsations which occur as the flux varies its path from tooth to tooth within the span of the coil will not affect the voltage of the coils. The only pulsating effect to be considered will be that which occurs in the two outermost teeth of those embraced by the coil, since this is due to an oscillation of flux between these teeth and the next ones, *i.e.*, an oscillation of flux across the conductors of the coil. It is evident that if the pulsations occur simultaneously at both ends of one coil, equal voltages will be generated which will cancel one another, unless the polarity of the fluxes are opposite, in which case the two voltages will be added. Now, this condition obtains in the case of coil *c*, which has a span of exactly one pole-pitch, and which should, therefore, show a pulsation voltage, due to the joint action of the fluxes, which simultaneously enter the first tooth at one side of the coil and leave the last tooth at the other side. We might, therefore, expect that the voltage of coil *c* would show a voltage approximately double that of coil *j*, which was wound round a single tooth, and which was, therefore, acted upon by only one such flux. On referring to Fig. 5, and making allowance for the difference in the air-gap induction for the two coils, it is seen that the voltage of coil *c* does actually rise above that of the adjacent coils by about twice the voltage of coil *j*. The coils of wider span are much more affected by the other irregularities of the rotating field than the narrow coils (such as coil *j*), which are hardly affected by them at all.

It has already been stated that the "saw-tooth" character of the voltages shown in Figs. 4 and 5 is due to flux pulsation in the teeth. This action may be regarded in the following general manner. Since each coil is wound in two slots, there will be two sets of voltages induced in the coil by the passage of the rotor teeth past these slots. The phase relation between these high-frequency voltages must depend on the span of the coil when expressed in terms of rotor teeth. If the span of the coil is such that its sides pass simultaneously under rotor teeth, so that the two sets of voltages are in phase, the resultant coil voltage will be a maximum. If the conductors at one end of the coil enter the

flux of a tooth at the same time as the other end is leaving the flux of a tooth, the induced voltages will largely neutralise one another. The resultant voltage of any coil due to flux pulsations depends, therefore, upon whether it embraces a whole or a fractional number of rotor teeth. Further, in the event of the conductor of a coil entering the flux of two rotor teeth simultaneously, the resultant voltage will have a maximum or a zero value, according as the fluxes of the two teeth are of identical or of opposite polarity. For coils having a span approximately equal to the pole-pitch of the motor, the pulsating flux at the two ends will be of opposite polarity. Hence, for such coils (which may be taken to represent the usual type of winding of a motor), a span which is an exact multiple of the pitch of the teeth which rotate relatively to it will be the seat of a maximum resultant E.M.F. On the other hand, coils which have a pitch of less than one-half of the pole-pitch, will have a maximum voltage when the number of teeth embraced is a whole number *plus* a half (as in coils *g*, *h*, *i*, *j* in the motor experimented upon), since the flux at the two ends of these coils will on the whole be of the same polarity. Applying this explanation to the curves given in Figs. 4 and 5, we remember that the stator on which the search coils are wound has 60 teeth, while the rotor has 48 teeth on its circumference. Coil *a* has a span of 19 stator teeth, corresponding to $19 \times \frac{48}{60}$ or 15·2 rotor teeth. This being nearly a whole number, we find a fairly high resultant voltage in this coil. By a similar calculation the span of coil *b* is equal to 13·6 rotor teeth, which, being nearly a whole number *plus* a half, gives a low resultant voltage. Coil *c* embraces exactly 12 rotor teeth and shows a high resultant voltage, while coil *d* shows a low value, since its span is equal to 10·4 rotor teeth. Coil *e* again corresponds to nearly a whole number of rotor teeth, viz., 8·8, and accordingly has a high voltage.

Coming now to the coils of smaller span, these show a uniformly lower voltage, due partly to the lower induction in that part of the air-gap in which they are situated caused by the longer air-gap at this point, to which allusion has already been made. This effect is magnified in the present case owing to the low induction (corresponding to 155 stator volts) employed. Also, in the case of those coils which have a span nearly equal to half the pole-pitch, the polarity of the flux cutting the two ends of the coils will be alternately of an opposite and of an identical character, tending to produce voltages which are alternately in series and in opposition. The virtual voltage due to flux pulsations is therefore reduced, whatever relation exists between the span and the number of teeth embraced (coils *f* and *g*).

The spans of the coils forming the second group have the following values :—

f	corresponds to	7·2	rotor teeth,	giving	1·1	volts.
g	,,	5·6	,,	,,	2·4	,,
h	,,	4·0	,,	,,	1·7	,,
i	,,	2·4	,,	,,	3·05	,,
j	,,	0·8	,,	,,	2·3	,,

It is to be noticed in the case of these coils that those embracing an exact number of rotor teeth show low resultant voltages, whereas those corresponding to an odd number of half teeth give higher voltages. This is in accordance with the discussion given on pages 141 and 142. A somewhat fuller discussion of these voltages will be found in Appendix B.

Returning to the two curves of stator voltage shown in Fig. 4, it is now easy to see why the voltages in the stator search coils are modified by the rotation of the open-circuited rotor. The flux pulsations which we have been considering must exist in the stator teeth as well as in the rotor, and will induce high-frequency harmonics of voltage in the stator windings. It is thus evident that the voltage in each search coil is the sum of that indicated in Fig. 3, observed with the rotor stationary, having a frequency of 50 cycles per second, and of a smaller high-frequency voltage of approximately $9{\cdot}5 \times 300/233 = 12{\cdot}25$ volts (see Fig. 5).*

The stator voltage under rotation is therefore made up as follows :—

$$\sqrt{(31{\cdot}6)^2 + (12{\cdot}25)^2} = 35 \text{ volts,}$$

a result which is in close agreement with the curve.

Results obtained by Grouping Coils.—Having considered the voltages developed in the individual coils, the next step was to investigate the effect of connecting a number of coils in series to form a complete winding. This was done by joining together several search coils in series and observing the voltage of the combination. With the supply on the stator, the voltage of the grouped coils was almost identical with that previously observed with the rotor stationary, the higher harmonics of voltage being too small in amplitude to have any appreciable effect.

When the motor was run at synchronous speed with the supply on the rotor, the results shown on Fig. 6 were obtained. These should be compared with the values of the separate coil voltages obtained under the same conditions and shown in Fig. 5. It is at once evident that the resultant voltage induced by field irregularities in several windings connected in series bears very little relation to the voltages of the individual windings, and is in general much smaller. This effect can be shown to be due to the fact that there are always voltages induced in some coils which are in direct opposition to those being simultaneously generated in others.

In order to form an idea of the way in which the voltages in successive coils are added on connecting them in series, we may proceed in the following approximate manner. Taking the central coil *c* having a span of 15 stator teeth, its arc of embrace equals the pitch of 12 rotor teeth. The pulsation voltages in the two slots in which this coil is wound will thus be nearly in phase with one another, but not quite, on account of the slot opening, which makes one voltage a little later than the other. The value of the resultant voltage at synchronism is seen from Fig. 5 to be 9·5. As an approximation, we shall assume that this is all due to flux pulsation in the teeth. Since each stator tooth-pitch

* The multiplier $\frac{300}{233}$ is required to make the values in Fig. 5 correspond to normal voltage.

corresponds to $\frac{1}{5}$ of a rotor tooth-pitch, the two voltages in coil *b* (having a span of two stator teeth more than coil *c*) will be respectively $\frac{1}{5}$ of a cycle in advance and $\frac{1}{5}$ of a cycle behind the corresponding voltages of coil *c*. Thus, assuming the same value of tooth induction, the voltage of coil *b* should be :—

$$9{\cdot}5 \cos (\tfrac{1}{5} \times 360^\circ) = 9{\cdot}5 \cos 72^\circ = 3{\cdot}8 \text{ volts.}$$

By similar reasoning, and again assuming the same value and phase of the flux in the teeth which simultaneously cut the coils, the resultant voltage in coil *a* should be—

$$9{\cdot}5 \cos (\tfrac{3}{5} \times 360^\circ) = 9{\cdot}5 \cos 216^\circ = -7{\cdot}7 \text{ volts.}$$

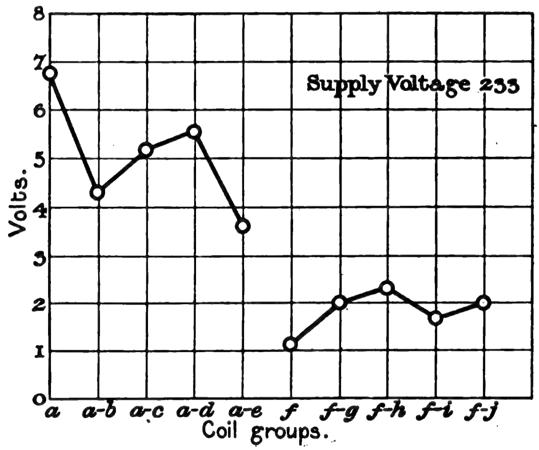


FIG. 6.—Search Coil Voltages in Rotor of Synchronously Running Motor.

Similarly the voltage of coil *d* would have a value 3·8 and that of coil *e* — 7·7 volts. These values are seen to have only a rough general agreement with the experimental ones given on the curve. This is indeed all that was to be expected, as we have neglected the phase difference in the voltages due to the sinusoidal variation of the flux round the air-gap, as well as that due to the width of the slot opening, and the effects of the want of constancy of the rotating field. If the actual voltages in the coils had the values just obtained from our rough calculation, we should obtain as the voltages of the coils when connected in series the following values :—

Coil *a*	... ...	$-7{\cdot}7$ volts.
Coils $a+b$	... ... $-7{\cdot}7+3{\cdot}8=$	$-3{\cdot}9$,,
Coils $a+b+c$	... ... $-7{\cdot}7+3{\cdot}8+9{\cdot}5=$	$+5{\cdot}6$,,
Coils $a+b+c+d$	... $-7{\cdot}7+3{\cdot}8+9{\cdot}5+3{\cdot}8=$	$+9{\cdot}4$,,
Coils $a+b+c+d+e$	$-7{\cdot}7+3{\cdot}8+9{\cdot}5+3{\cdot}8-7{\cdot}7=$	$+1{\cdot}7$,,

Here again we have only a very rough resemblance to the experimental values as given on Fig. 6, but sufficient to show the chief factor which governs the results obtained.

The voltages induced in the grouped coils when the motor was running under load are shown in Fig. 7.

The results just arrived at are not without practical importance, since they have a direct bearing on the question of wound rotors *versus* squirrel-cage rotors for short-circuited induction motors. For example, in Fig. 5 we see a pulsation voltage of 9·5 volts induced in the coil wound in a pair of slots having a pitch equal to that of the poles of the motor. This corresponds to nearly 1 volt per turn at the normal voltage. If such a coil were directly short-circuited on itself, as would virtually be the case in a squirrel-cage motor, we should probably obtain a considerable current of high frequency which would not contribute to the torque of the motor. By connecting in series the

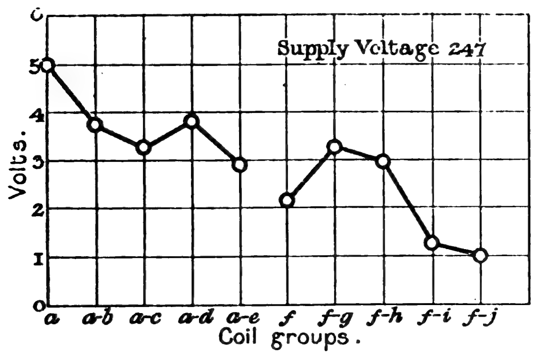


FIG. 7.—Search Coil Voltages in Rotor under Load.

conductors in several slots, we see from Fig. 6 that the resultant voltage due to irregularities of the field is much decreased, while at the same time the impedance of the circuit in which this voltage acts is largely increased. The pulsating currents and the heating due to them may thus be reduced to a relatively small value in a wound rotor. On short-circuiting the rotor winding of the induction motor under consideration, while driven at synchronous speed, the slip-ring current was found to have a value of just less than 1 ampere, although the open circuit slip-ring voltage was over 4 volts.

It will be seen from the results that the damping out of high-frequency voltages in the rotor winding depends less on the number of slots per phase than on the relation existing between the spans of the several coils. The same consideration will govern the extent to which the effects of "cogging" will make themselves felt, when full speed has been obtained. In most motors the magnitude of the voltages which are induced in the separate rotor coils is masked by the

differential action between the coils, which makes it impossible to measure them. It is, however, evident that the slip-ring voltage at synchronism gives very little information as to the actual amplitude of these pulsations.

Oscillograph Records of Induced Voltage in Search Coils.—It will now be of interest to compare the oscillograph records of the voltages in the various search coils with the virtual values which we have been discussing. These records were taken under exactly the same conditions as the readings of the virtual values shown on Figs. 5 and 6. The motor was driven at synchronous speed by a synchronous machine, the stator being unexcited, while the rotor was supplied with current at the slip-rings so as to produce a rotating field which was stationary in relation to the stator and to the search coils mounted upon it.

The series of curves reproduced in Figs. 8 to 15 show the wave-form of the voltages whose virtual values are plotted in Fig. 5, and illustrate the character of the electromotive forces induced in the rotor

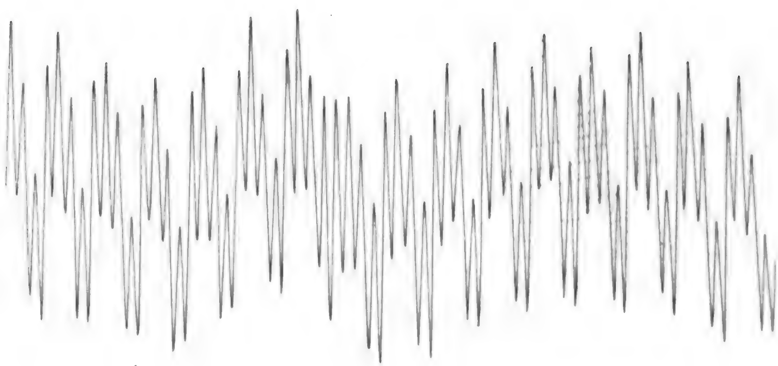


FIG. 8.—Voltage in Search Coil *a*, embracing 19 Stator Teeth.

of an induction motor by the irregularities of its rotating field. The scale of all the curves is not the same, but the relative amplitudes of the waves can be approximately judged from the effective values given on Fig. 5. An examination of the curves shows that they all consist of a combination of three principal harmonics, and that the differences between them are due to the variety in relative amplitude possessed by these harmonics. These three harmonics are :—

1. A fundamental, or first harmonic, having the frequency of the supply, well-marked in Figs. 9 and 10, which each comprise about 2½ wave-lengths of the fundamental. The amplitude of this variation shows the extent of the change in strength of the flux per pole of the motor.

2. A sixth harmonic, which shows prominently in the curves of Figs. 11, 13, 16, and 17. This is due to the variation in the field produced by the excited winding, and is not caused by flux pulsation.

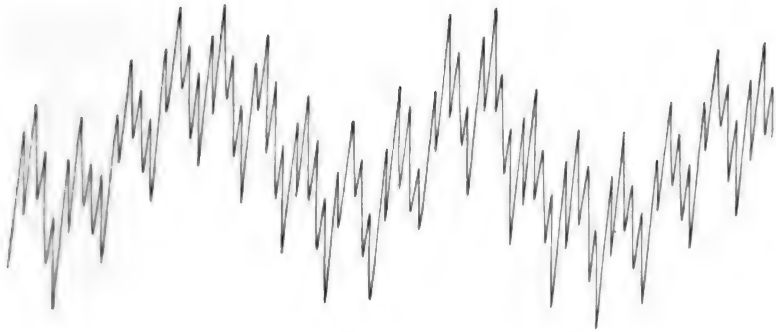


FIG. 9.—Voltage in Search Coil *b*, embracing 17½ Stator Teeth.

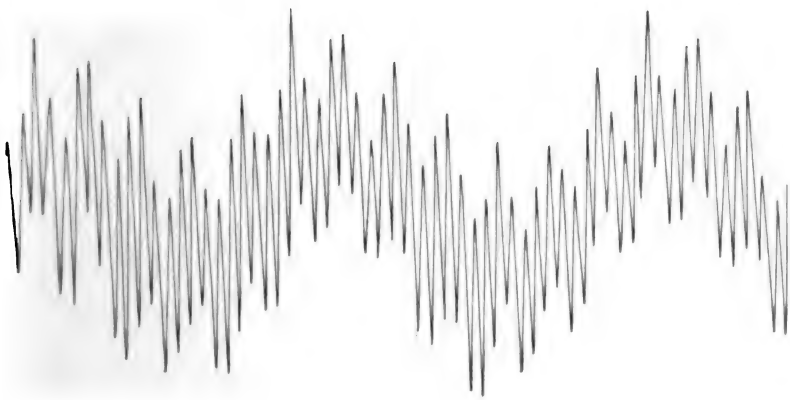


FIG. 10.—Voltage in Search Coil *c*, embracing 15 Stator Teeth.

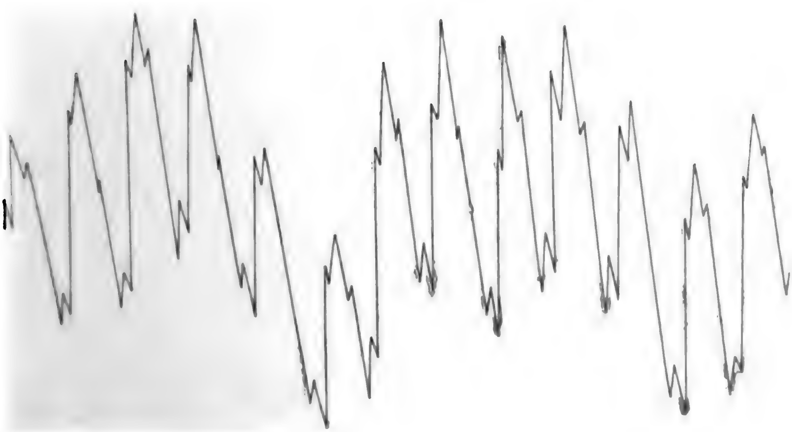


FIG. 11.—Voltage in Search Coil *d*, embracing 13 Stator Teeth.

It shows, in fact, the influence of the changes of maximum induction and speed of the field which are most strongly marked at 12 points of the motor circumference (see page 133).

3. A twenty-fourth harmonic due to flux pulsation, and dependent for its period on the number of teeth acting upon the winding—in the present case twenty-four per pole-pair of the motor. This harmonic can be traced in all the curves, except Fig. 17, and is specially well marked in Figs. 8, 9, 10 and 12.

The voltages which have a high effective value, *e.g.*, curves of coils *a*, *c*, and *e*, are seen to be distinguished from the others mainly by the greater amplitude of the component due to pulsation. As already shown, the span of these coils corresponds nearly to a whole number of rotor teeth. In coils *b* and *d* we have examples of the differential action occurring between the two ends of coils which span an odd number of half-teeth. The oscillations are no longer free and of equal length, but are very unequal, the majority being of small amplitude. These curves are typical of the rest, which resemble one or the other in varying degree.

Figs. 16 and 17 show the voltages in coils connected in groups. The harmonics due to pulsation are here of small amplitude, since those generated in successive coils are in mutual opposition. The more important of these is the group *a* to *e* in Fig. 16, since this shows the voltage of the search coils occupying the same slots as the actual coils of the stator winding. We still see the same 48 peaks in the time of one complete wave of the fundamental, although their amplitude is much reduced, the scale of this curve having been increased in order to make the curve clear. Each peak must in fact be looked upon as representing a voltage which is the vector sum of ten separate voltages formed in separate slots, and which are out of phase with each other in varying degrees.

The question naturally occurs: To what extent can the oscillations observed in the search coils which are wound close to the mouth of the slots be taken to represent the flux variations occurring in the body of the teeth and acting on the actual motor winding? The answer to this seems to be that the effects observed are not confined to the surface of the core, but are substantially the same as those which are experienced by the winding itself. This was tested by comparing the synchronous voltage induced in the stator winding with that measured in the search coils wound in the same slots, and also by taking curves of the rotor voltage on the oscillograph in the same manner as on the search coils. A comparison of the virtual voltages measured on the search coil and stator winding respectively showed that the flux pulsations affected both in practically the same degree, while the oscillograms taken on the two windings are almost identical.

The importance of employing a sinusoidal voltage in the experiments was found, for on applying a voltage to the motor derived from an alternator giving a somewhat peaked and otherwise less regular wave-form, the curves observed in the search coils were of such a

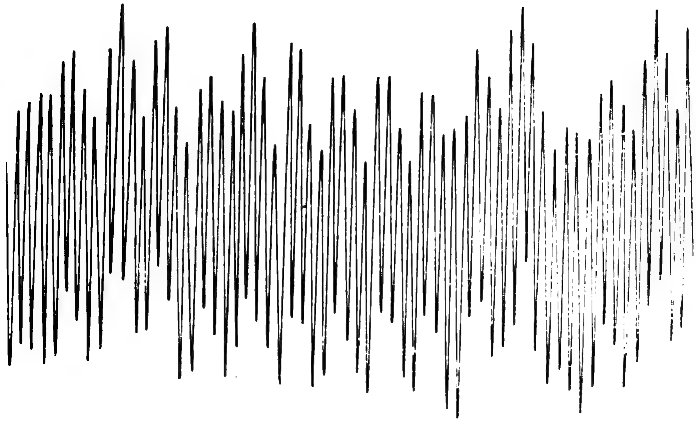


FIG. 12.—Voltage in Search Coil *e*, embracing 11 Stator Teeth.

FIG. 13.—Voltage in Search Coil *f*, embracing 9 Stator Teeth.

FIG. 14.—Voltage in Search Coil *h*, embracing 5 Stator Teeth.

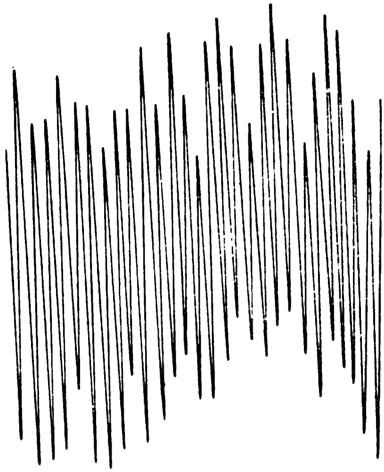


FIG. 15.—Voltage in Search Coil j, embracing 1 Stator Tooth.

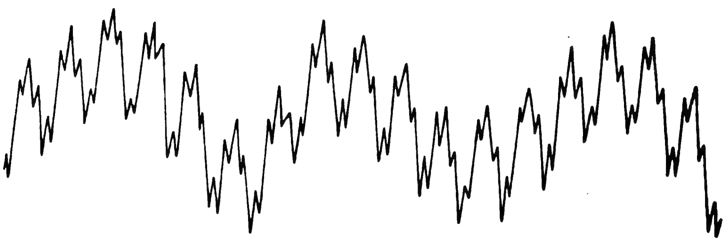


FIG. 16.—Voltage in Search Coils a to c, connected in Series.

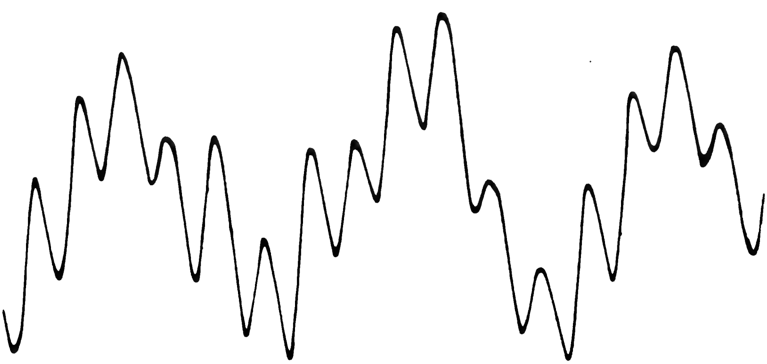


FIG. 17.—Voltage in Search Coils f to j, connected in Series.

complicated form as to make it practically impossible to assign definite origins to the various harmonic waves.

Further Tests on another Motor.—In order to confirm the general conclusions drawn from the tests already described, a further set of search coils were wound on another motor having a different type of winding and a different construction in other respects. The motor chosen for this purpose was a 6-pole 5-H.P. motor made by Siemens Bros., having 54 stator slots, 29 conductors per slot, and 39 rotor slots with 4 conductors per slot. The stator winding was carried out with 3 coils per pole and phase, 3 sets of coils being connected in series to form each phase-winding. The voltages measured in the search coils of this motor were similar in their relations to those already discussed and do not call for any special mention, except as confirming the conclusions previously arrived at. The voltages generated in these coils corresponded in every way with those already observed in the three central coils, *b*, *c*, *d*, of the other motor.

Interesting results were obtained bearing on the distribution of the stator voltage between the several coils which are connected in series to form the stator winding.

Effect of Uneven Air-gap.—The stator winding of an induction motor is necessarily formed of several coils connected in series, and the voltage applied to the stator will be divided equally between these coils, if the induction in each is the same. If, however, the air-gap of the motor is not uniform, the voltage will be distributed between the coils approximately in the ratio of the flux densities at the points where the coils are situated—that is, roughly in the inverse ratio of the air-gap lengths at these points. It must frequently occur that through wear of the bearings and other causes, the air-gap of an induction motor is not uniform all round the rotor, and the author believes that it is not generally realised how few of these motors have an air-gap which is sufficiently uniform to give an approximately constant induction in all directions. Mr. Miles Walker has told the author that with liberally designed bearings the wear should be practically nil, although cases do arise where unfair conditions have caused the rotor to sink sufficiently to touch the stator. Large induction motors are made with adjustable bearings, and the air-gap is supposed to be corrected before it has become reduced by more than 15 per cent. He has found in ordinary shop practice that the air-gap will sometimes be 15 or 20 per cent. out of truth. In motors examined by the author, in actual service, an even larger discrepancy has been found.

It would be easy to over-estimate the importance of this want of uniformity of the field, but it may be worth while to enumerate the disadvantages likely to arise from it, viz.:—

1. The magnetic drag on the rotor in the direction of the strongest field.
2. The concentration of the applied voltage in certain coils of the winding, producing unequal dielectric stresses.

3. Increased hysteresis and eddy-current loss in the teeth subjected to high induction.
4. Unequal voltages in the phases of the rotor resulting in an unsymmetrical distribution of currents, varying with the frequency of rotation.

Evidently, these points are all arguments in favour of using as large an air-gap as possible, in order that an unavoidable inequality may have a small relative value. The calculation of the magnetic pull due to the eccentricity of the rotor is dealt with in a paper by Rey.*

Coil Voltages in Non-uniform Air-gap.—It has already been mentioned that the break of the curves of Fig. 3 was due to the unequal lengths of the air-gap in the two positions occupied by the coils. The extent to which the unevenness of the air-gap modified the voltage distribution

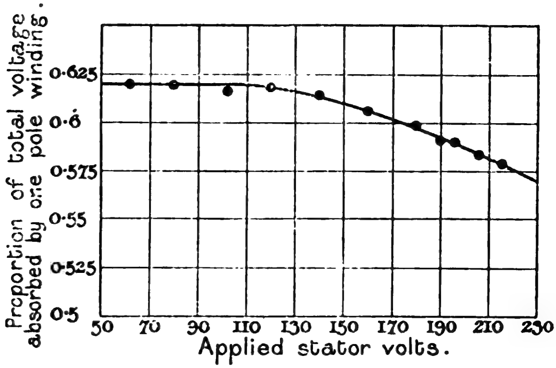


FIG. 18.—Illustrating Uneven Distribution of Applied Voltage in Stator Winding.

in the phase winding of this motor may be seen from Fig. 18. Here the portion of the total phase voltage absorbed by one pole-winding is plotted on a base of supplied volts. The volts taken by the pole-winding were calculated from the induction in the search coils wound in the same slots, while the motor was stationary with open-circuited rotor.

The winding embraced a part of the stator where the air-gap was small, and the droop in the curve shows the effect of the earlier saturation of the teeth at this point.

A somewhat similar result, taken on the 5-H.P. Siemens motor, already mentioned, is shown by the three curves in Fig. 19.

In this case three sets of search coils were wound on the stator in the same slots as the conductors of the stator windings of the motor. The positions of these search coils corresponded with the coils of one complete phase-winding of the stator, so that the relative voltages

* *Éclairage Électrique*, vol. 38, p. 281, and vol. 41, p 257, 1904.

induced in these three coils could be taken to represent the relative inductions at the three points of the stator occupied by one phase-winding, and also the proportion of the applied voltage absorbed in the several coils of this phase. The motor chosen had a very small air-gap—viz., 16 mils. Owing to wear of the bearings, the motor had sunk 3 mils, leaving an air-gap of 19 mils at the top and 13 mils at the under-side of the rotor.

The induction at three different points of the stator was first found without current in the rotor, by supplying the stator with a gradually increased voltage and observing the volts induced in the three search

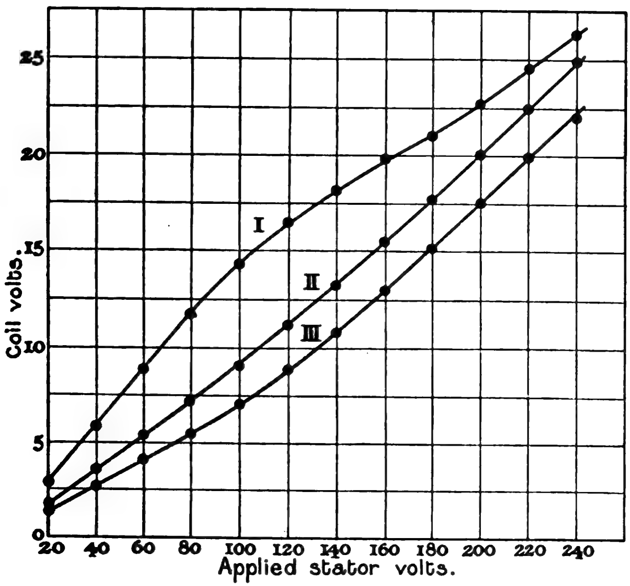


FIG. 19.—Relation between the Voltages of the three Pole-windings of the Stator.

coils. The readings of the coil voltages are given in Fig. 19, where 200 volts represents the normal stator voltage. The two lower curves are the readings of coils situated near the top of the stator and consequently in a part of the air-gap larger than the normal. The upper curve is that of a coil in an abnormally small air-gap.

The effect of the saturation of the teeth in modifying the voltage distribution is very clearly shown, and it is evident that the teeth at the bottom of the stator are very highly saturated.

The effect of rotation and of load on the distribution of the voltage in the coils was very slight.

In one of the other phases of the same motor two pole-windings

were near the bottom, while only one was in the less dense field at the top, producing the result of a smaller total reactance in this phase.

In comparing these curves with the previous ones shown on Fig. 18, it may be noted that the drop in the rotor is the same in both cases, but that the initial air-gap of the Siemens motor was smaller and the effect of the rotor eccentricity was consequently greater.

Effect of Uneven Air-gap on Motor Output.—The experiments already described were sufficient to show that an uneven air-gap may produce inequality in the rotor phase voltages, especially where the number of pole-windings is small. The position of the search coils did not permit of an examination of the actual irregularities introduced in the rotor voltage or current by rotation in an air-gap of varying length. From measurements of the rotor voltage and current with the rotor stationary and in different positions, a variation of about 5 per cent. was found, most of which was probably due to this cause.

It seems highly probable that an unbalancing of the rotor phase voltages should be accompanied by an increase in the losses of the motor, and that the greater the number of closed circuits in the rotor winding, the greater would be the liability for such losses to occur. Thus we might expect greater losses from this cause in a motor with mesh-connected rotor than in a star-connected rotor, and greater losses still in a squirrel-cage motor having the same degree of eccentricity. In this connection it may be worth while to refer to a paper by Messrs. Hillebrand and Charters,* in which they describe experiments upon the effect of an out-of-balance in the voltage applied to the stator of an induction motor. They found that the output of the motor was decreased considerably by inequality in the voltage or power factor of the phases of the supply. A voltage out-of-balance of 5 per cent. produced something like 15 per cent. decrease in the output of the motor.

Osnos † has called attention to the heavy equalising currents which may be set up in the rotor of a squirrel-cage motor, if the rotor is not central, and has proposed special means for reducing these. In the case of wound rotors, it is probable that the increase in the iron losses is more important, although an increase in the rotor copper losses, due to circulating currents, is to be expected.

In conclusion, the author wishes to make acknowledgment to the Principal and Committee of the Municipal School of Technology, Manchester, where the experiments described in this paper were carried out. For assistance in the experimental work, he desires to thank his colleague, Mr. W. Grant, and Mr. P. E. Bamford, a former student of the Schools, for much painstaking work in connection with the measurements, as well as Mr. J. Davies for help in taking the oscillograph records.

* *Transactions of the American Institution of Electrical Engineers*, vol. 28, pt. 2, p. 1253, 1909.

† *Zeitschrift für Elektrotechnik*, vol. 20, p. 389, 1902.

APPENDIX A.

Calculation of Coil Voltages.

The voltages induced in coils of different spans may be calculated as follows on the assumption of a sinusoidal field distribution :—

Let—

$E \sin \theta$ represent the voltage induced in the conductors of one half of the coil,

then—

$E \sin (\theta + \pi + a)$ will be the voltage simultaneously induced in the other side of the coil,

where—

$a =$ the electrical angle spanned by the coil.

These two voltages will act in the same sense round the coil, so that the resultant voltage at any instant will be—

$$E\ [\sin \theta + \sin (\theta + \pi + a)].$$

The virtual value of this voltage will be—

$$\sqrt{2}\ E \cos \left(\frac{\pi + a}{2}\right).$$

In the present instance the motor is 4-pole and has 60 stator teeth ; consequently, each tooth-pitch corresponds to $\frac{720}{60} = 12^\circ$ of phase angle.

We may therefore write the virtual voltage of a coil embracing m teeth as—

$$e \cos (90^\circ + 6\, m^\circ),$$

where e is the voltage induced in a coil having a span of one pole-pitch.

The voltages in the coils of various spans will then have the following values expressed in terms of the voltage of coil c, which has a span of 15 stator teeth, exactly equivalent to one pole-pitch :—

Coil.	Span in Stator Teeth.	Voltage as Function of that of Coil c.
a	19	$\cos 24^\circ = 0{\cdot}914$
b	17	$\cos 12^\circ = 0{\cdot}978$
c	15	$\cos 0^\circ = 1{\cdot}000$
d	13	$\cos 12^\circ = 0{\cdot}978$
e	11	$\cos 24^\circ = 0{\cdot}914$
f	9	$\cos 36^\circ = 0{\cdot}809$
g	7	$\cos 48^\circ = 0{\cdot}669$
h	5	$\cos 60^\circ = 0{\cdot}500$
i	3	$\cos 72^\circ = 0{\cdot}309$
j	1	$\cos 84^\circ = 0{\cdot}105$

The observed values of the voltages of the last five coils were less than the calculated values on account of the smaller induction in the part of the air-gap in which they were situated.

APPENDIX B.

Calculation of Voltage Due to Flux Pulsations.

The voltage produced in the stator coils as a result of the flux pulsations in the stator teeth set up by the rotation of the rotor may be calculated as follows, on the assumption that other disturbing factors are absent.

Let $E \sin \delta$ be the voltage induced by the passage of the pulsating flux across the conductors forming one side of the coil.

δ is a varying angle which passes through one complete period in $\frac{1}{n\,m}$ second,

where—

$n =$ revolutions per second of rotor.
$m =$ number of teeth possessed by rotor.

Assuming the two sides of the coil to be situated in equal fields of the same polarity, the voltage simultaneously induced in the opposite side of the coil and in the same sense round it would be—

$$E \sin (\delta + \pi + 2\,\pi\,m_2),$$

where $m_2 =$ number of rotor teeth in the coil span.

Since, however, the flux crossing the conductors at the two sides of the coil will not generally have the same value, there will be a further relative phase displacement between the two electromotive forces due to this cause.

This displacement will have a value—

$$\frac{2\,\pi\,p\,M_1}{M}$$

where—

$p =$ number of pole-pairs of motor.
$M =$ total number of stator teeth.
$M_1 =$ number of stator teeth in span of coil.

The voltages in the two sides of the coil may, therefore, be written—

$$E \sin \delta \quad \dots \dots \quad (1)$$

$$E \sin \left[\delta + \pi + 2\,\pi \left(m_2 - \frac{p\,M_1}{M} \right) \right] \quad \dots \dots \quad (2)$$

The virtual value of the resultant voltage due to these two acting in the same coil will be—

$$e = \sqrt{2}\,\mathrm{E}\cos\pi\left(m_2 - \frac{p\,\mathrm{M}_1}{\mathrm{M}} + \tfrac{1}{2}\right).$$

In the present case, since the rotor had 48 teeth, and the stator 60 teeth, we may write for m_2 the value $\frac{48}{60}\,\mathrm{M}_1 = \frac{4}{5}\,\mathrm{M}_1$.

So that by substituting $p = 2$ and $\mathrm{M} = 60$, we have—

$$e = \sqrt{2}\,\mathrm{E}\cos\pi\,(0{\cdot}767\,\mathrm{M}_1 + \tfrac{1}{2}).$$

This will have a maximum value for coil c, when M_1 is 15.

Taking the pulsation voltage in coil c as unity, the corresponding voltages in the ten coils of different spans will be as follows :—

Coil Letter.	Span in Teeth.	Pulsation Voltage.	Coil Letter.	Span in Teeth.	Pulsation Voltage.
a	19	−0·980	*f*	9	− 0·31 (− 0·214)
b	17	+ 0·096	*g*	7	+ 0·92 (+ 0·613)
c	15	+ 1·000	*h*	5	+ 0·5 (+ 0·337)
d	13	+ 0·096	*i*	3	− 0·81) − 0·54)
e	11	− 0·980	*j*	1	− 0·67) (− 0·447)

The last five coils were situated in a part of the air-gap having a flux only about two-thirds of its value in the position occupied by the first five coils. On reducing the voltages for these coils in this ratio we obtain the values given in brackets in the table.

The pulsation voltages just calculated are plotted in Fig. 20, which should be compared with Fig. 5. Such a comparison shows how the voltages in the coils with a wider span are increased in the actual motor by the other irregularities of the field, as is also evident from the oscillograph curves. The actual value of this added voltage in any particular coil depends upon the position of the coil relatively to the field, and has a different value for each coil. In the conditions under which the oscillograph curves in the paper were taken, the sixth harmonic appears with special prominence in certain coils, whereas with another position of the stationary field other coils would have these harmonics most prominently.

Thus, not only the amplitude, but also the form of such curves as that shown in Fig. 6, in which the coils are grouped, varies with the relative position of the field and stator. The oscillograph curves taken on the grouped coils show that the harmonics of lower frequency are

damped out to a less degree than those due to the high-frequency flux pulsations. The resultant voltage of a group of coils is thus chiefly determined by the harmonics of the 1st and 6th order.

APPENDIX C.

Variations in the Rotating Field due to Different Numbers of Stator Slots.

(*Abstracted from an article in the "Elektrotechnische Zeitschrift," vol.* 22, p. 274, 1901, by J. B. Krantz.)

(*a*) The maximum induction in the teeth of the stator is different for teeth in various positions on the stator, and has its greatest value in those teeth which lie between two adjacent phase windings, and its least value in teeth which lie at the centre of a coil.

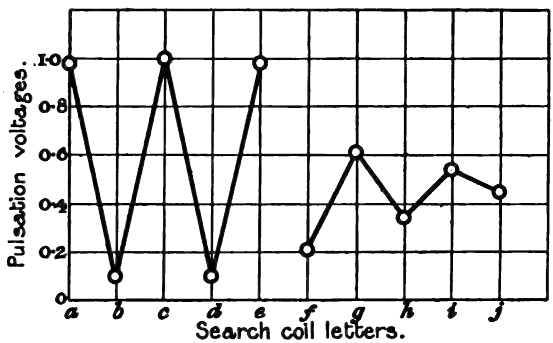


Fig. 20.—Calculated Voltages due to Pulsation.

The ratio of the maximum induction in teeth lying between the coils to that of the teeth situated at the centres of the coils will have the value indicated by p in the annexed table, for various values of the number of slots per pole and phase.

The ratio of the maximum flux per tooth to the average flux per tooth of the motor is given in column c in the table. (By the term flux is meant the maximum value of the flux during a cycle.)

(*b*) The speed of the rotating field varies, having a maximum value at points in the stator where two coil windings meet, and a minimum value at the centres of the spaces occupied by the coil winding.

The ratio of the least to the greatest angular velocity is given in the table under r.

(*c*) The total flux per pole varies slightly during each cycle; the ratio of maximum flux to minimum flux is given in the table under s.

(*d*) Finally, the E.M.F. of a winding may be calculated from the product of the flux of each tooth by the number of windings of one phase with which the flux is linked.

Assuming a sinusoidal variation of the flux, the value of the E.M.F. is given by a formula of the form—

$$E = k \sim F N \times 10^{-8},$$

where—

F is the average value of the maximum flux per tooth.

N is the number of conductors composing the winding which the flux links.

k is a coefficient given by the following table :—

q	*p*	*r*	*s*	*c*	*k*
1	1·000	1·00	1·000	1·50	2·22
2	1·154	1·33	1·005	1·65	2·15
3	1·134	1·29	1·008	1·69	2·13
4	1·154	1·33	1·009	1·70	2·13
5	1·147	1·32	1·009	1·71	2·12
6	1·154	1·33	1·009	1·71	2·12
7	1·151	1·32	1·009	1·71	2·12
∞	1·154	1·33	1·010	1·71	2·12

Discussion before the Manchester Local Section.

Mr. W. Cramp: The development of electrical machinery has advanced so far that very little in the way of absolutely new machines can be expected, and, in consequence, we are very much indebted to any one who will give the time and patience to a detailed examination of any conditions affecting the performance of well-known apparatus. Such work must lead to small but radical advance, though the amount of work involved in what seems a small accession of knowledge is very large, as is clear from the paper. For instance, on page 148 it would seem that a very large number of experiments have been carried out, of which, I think, only the general results are given. Now, of the many issues in the paper requiring further explanation, I will select one or two which seem to me very important. On page 137, under the heading of "Grouping of Coils," we find the statement, "On connecting the search coils belonging to one pole together in series, the resulting voltage was found to be equal to the arithmetic sum of the voltages of the individual coils. This was to be expected." Now, I do not find any clear evidence in the paper as to the saturation of the teeth, and it seems necessary to point out that the above result was *not* to be expected, except on the assumption of fairly low tooth densities. On page 134 mention is made of a motor which has been particularly tested. The machine had 60 slots in the stator and 48 in the rotor, and it had 4 poles—that is, 15 and 12 slots per pole respectively. Now, the greatest Mr. Cramp.

Mr. Cramp. common factor of these two numbers is 3. I call attention to this matter here because it affects the results throughout the paper, though I do not find any reference to this G.C.F. by Mr. Smith. The author, on page 139, in giving reasons for variations in voltage, omits altogether any reference to pulsation produced by eccentricity of the rotor with respect to the shaft. In some cases I have found such lack of truth to be very important. On page 139 also I would call attention to the very beautiful method employed to obtain the effect of the pulsations by eliminating the main rotating field. I think that the agreement in form between Figs. 3 and 5 is very good as bearing witness to the truth of the explanations offered for the effects noticed. On the bottom of the same page we read: "The conditions under which the readings of Fig. 5 were taken were such as to make the voltage of coil *c* a maximum—that is to say, the conductors of this coil must have been situated at points of maximum flux." Here there seems to be an error. When the voltage of coil *c* was a maximum, the rate of change of flux through it was a maximum, of course; but it does not seem to me to follow that the flux itself was a maximum. On page 141 the effect of flux pulsation on coil voltages is discussed, and Mr. Smith approaches this question from the point of view of the flux per tooth. I venture to think that, though that method may be right in the present case, there is a further effect not considered. I think that a component of the pulsating voltage might be due to the number of times per second there was a correspondence between the rotor and the stator teeth. It does not follow that this change would correspond with the flux moved per tooth. Perhaps the case is more easily illustrated if we imagine a 2-pole motor with one stator coil per phase, and as many teeth in the rotor as there are in the stator. Under those conditions at one instant the whole of the teeth will correspond all round. The next instant the teeth of the rotor will be opposite the slots in the stator, and that change of flux need not correspond to the flux which actually passes across the slots, as described in the paper. The effect to which I refer is thus seen to be dependent on the G.C.F. between the stator slots per pole and the rotor slots per pole. On page 151 there are given some tests on a Siemens motor which had 54 stator slots and 39 rotor slots. In this case the G.C.F. is only 1, so that the results due to the effect I mention should be much smaller. On the same page the effect of uneven air-gap is mentioned, and I think it should be remembered that, even if the air-gap is uneven, as described, the effect will be smaller than Mr. Smith thinks, especially with a small number of poles, for the path of the flux involves crossing the gap twice, so that in a 2-pole case the increase in field strength, due to uneven air-gap, should be practically zero. Finally, we may consider the general bearing of the whole paper on induction-motor design, and I think we can come to but one conclusion, that pulsation voltages are of importance only in very high-pressure machines, and the average induction motor as at present constructed is, on the whole, wonderfully free from effects due to irregularities in its field.

Professor E. W. MARCHANT: I should like, in the first instance, to refer to some work that has been done by one of my former students, Mr. Lawson, who is, unfortunately, unable to be present this evening. In my laboratory at Liverpool, a good many tests have been made by him on the irregularities in the rotating field of induction motors, on much the same lines as those Mr. Smith has carried out. I hope Mr. Lawson will forward, as a contribution to the discussion, the results of some of his experiments on a 2-phase motor. These results will be of interest in comparison with those that Mr. Smith has obtained. I may just mention one point as to the effect which the load on the motor has of increasing the losses due to pulsations in the teeth of the induction motor. Mr. Lawson made a good many experiments on this, and found the increase in those pulsation losses very considerable, the magnetic pulsations in the teeth being in certain cases more than doubled under full load. The author gives us the figures for the voltage induced in the rotor on open circuit and the corresponding current. Of course, it is quite clear that under these conditions the frequency of the voltage which is induced in the rotor will be very high, since it is caused mainly by field irregularities due to the teeth, and therefore it is not surprising that the current which flows in this particular case is small, on account of the large impedance of the rotor to these currents. Professor Marchant.

Mr. Smith refers to four possible effects of an uneven air-gap. I think the first one is really of negligible importance, because the magnetic drag which is produced with an eccentric rotor depends simply on the hysteresis and eddy-current losses in the rotor, and therefore this magnetic drag is a small effect, and is taken account of in (3); the additional losses give lower efficiency and a diminished torque. Referring to "the concentration of the applied voltage in certain coils of the winding producing unequal dielectric stresses," that, I think, again is a really unimportant point, because we know that the inequality of the stresses that occur in an induction motor when it is switched on are very large as compared with any inequalities that can possibly be obtained from unequal distribution of the field. As to "unequal voltages in the phases of the rotor resulting in an unsymmetrical distribution of currents, varying with the frequency of rotation," this is, I think, one of the most important effects of an uneven air-gap that we have to consider. It should be noticed, however, that the effect due to eccentricity is only important if it produces unequal loading of the phases of the stator. The current in all the coils of any one phase must be the same, and therefore the corresponding rotor currents must be practically the same. If the currents in the three phases are different, however, unequal bands of rotor current are produced, which have the effect of causing useless circulating currents in the rotor conductors and consequent excessive heating of the rotor. This is emphasised by the illustration quoted by Mr. Smith at the end of his paper.

Mr. G. W. WORRALL: The subject of magnetic oscillations is Mr. Worrall.

Mr. Worrall of very great interest to me, and I am glad to see that the oscillograph and search coils have been brought into service to reveal the internal working of the polyphase induction motor, for I think that such a method of investigation is the most reliable and yields the most interesting results. Turning to the results obtained, I find a very interesting confirmation of some work I published in 1908. The machine I employed was a synchronous generator with rotating armature. By varying the width of the pole-face, I found that the magnetic pulsations as shown by a search coil wound round the pole-shoe, were a maximum when the polar arc was an exact multiple of the tooth-pitch, and a minimum when it was a whole number plus one-half. The electrical and magnetic conditions obtaining in such a machine appear to be similar to those in the induction motor as arranged for the experiments described by the author, for when the rotor rotates at synchronous speed, the field produced by a 3-phase current in the rotor windings is approximately stationary in space and constant in magnitude. The stator teeth will therefore cause no pulsation except as a function of any cyclic irregularity which may exist in the main flux. Since this latter is in any case very small, the influence of the stator teeth may be considered as a negligible quantity. The rotor teeth, however, are passing through the main field and will therefore set up pulsations. These pulsations will induce E.M.F.'s in a coil on the stator in exactly the same way as in the case of the pole-shoe coil in my own experiments, and should therefore be subject to the same law as regards the span of the coil. That this is the case may be readily seen from page 141, and the oscillograms given in Figs. 8 to 12. Here coils *a*, *c* and *e* span 15·2, 12 and 8·8 rotor teeth respectively, all of which numbers are nearly whole nnmbers, while coils *b* and *d* span 13·6 and 10·4 respectively, which may be written approximately as whole numbers plus one-half. In the former case the magnitudes of the oscillations are much greater than in the latter case, both in the oscillograms and in the actual voltmeter measurements given in Fig. 5. Thus the author's results and my own are in agreement. The influence of the stator teeth is of far greater import when the motor runs under normal conditions, for then the stator teeth are subject to the rotation of the main field at synchronous speed, and therefore produce pulsations in it in the same way as the rotor teeth do in the author's experiments. Under these conditions, however, the rotor teeth have far less import, for they are only subject to the main flux rotating at the speed of slip, hence the pulsations produced by them will be relatively small. Such conclusions assume that the two sets of teeth behave independently of each other, and although I am quite aware that this is not generally considered to be the case, my own observations of the behaviour of the magnetic flux between two surfaces separated by an air space lead me to believe that the two sets of teeth behave to a great extent in a manner independent of each other.

I certainly hope that the author will extend his experiments to the question of the influence of load and the relation between the stator

and rotor teeth. I would like to suggest that he employ some method of marking the relative positions of the stator, rotor, and field on the oscillograms, and also that the oscillograph be calibrated and the scale marked on each record, so as to render a comparison possible. Mr. Worrall.

Dr. E. ROSENBERG: I am in agreement with the remarks of the author that air-gaps of induction motors should not be taken too small. After all, mechanical reliability is, for the user, the most important feature of a motor, and it is not right to sacrifice mechanical reliability in order to improve the electrical performance. Certainly we want a good power factor, but we must not reduce the air-gap below the safe limits. I should say that in electrical machinery by far the greatest number of breakdowns is due to mechanical reasons. Excellent electrical performance shows up mainly on a test, like that of a good scholar at a school examination; but it does not necessarily follow that the pupil who makes the best show at an examination is the one who is most successful in life. I would like to take exception to the statement of Mr. Smith on page 145, "If such a coil were directly short-circuited on itself, as would virtually be the case in a squirrel-cage motor, we should probably obtain a considerable current of high frequency which would not contribute to the torque of the motor," and to a quotation from a paper by Osnos on page 154, who "called attention to the heavy equalising currents which may be set up in the rotor of a squirrel-cage motor, if the rotor is not central." I do not think that this equalising current would amount to any great value. Of course, if we divide the measured voltage by the resistance of the squirrel cage it would show the possibility of a very great current, but we must not forget that every equalising current at once reduces the fields which set up this voltage. If a fully excited alternator is on steady short circuit we do not get more than about twice normal current—that is to say, the full field of the alternator is practically wiped out by twice full-load current. Therefore we can see that the comparatively small fields which would produce in an open-circuited winding higher harmonics of only a few per cent. of the full open-circuit voltage of the rotor will be at once destroyed by very small equalising currents. Mr. Cramp suggested that the addition of currents of different frequencies, as shown on page 143 of the paper, would only be correct if the passing harmonics were sinusoidal waves, but this is not so. The resultant value of waves of different frequencies can always be taken as the R.M.S., whether each of the components is a simple harmonic or is in itself the R.M.S. value already of several components of different frequency. If one of the components is not a sinusoidal wave, this only indicates that the measured value of this component is itself a resultant of sinusoidal waves of different frequencies, and it does not matter whether the R.M.S. of all the different components is taken at once or taken in different steps, it always remains the same. Let us assume that four harmonics of different frequencies would have respectively the measured value of a, b, c, d, then we obtain the same result whether the operation is— Dr. Rosenberg.

$$\sqrt{a^2 + b^2 + c^2 + d^2};$$

Dr. Rosenberg. or whether we work in steps—

$$\sqrt{(\sqrt{a^2 + b^2})^2 + (\sqrt{c^2 + d^2})^2};$$

or—

$$\sqrt{(\sqrt{a^2 + b^2 + c^2})^2 + d^2}.$$

Mr. Frith. Mr. J. FRITH: I will confine my remarks to the effect of uneven air-gap. The author says, "The stator winding of an induction motor is necessarily formed of several coils connected in series." If this effect of unequal induction is really likely to be troublesome, we can connect the coils on the opposite side of the motor in parallel and not in series, and instead of having the magnetising current the same and the flux varying inversely with the clearance, we can put the same voltage across the coils, and then the flux is bound to be the same whether the rotor is central or not.

Mr. Aldous. Mr. F. C. ALDOUS: Referring to the decrease in output, it is a well-known fact that if the rotor of an induction motor is out of centre, and if the coils are connected in series, there is a higher flux on one side of the motor than on the other, causing an unbalanced magnetic pull, but any extra losses that are set up cannot be considered as important, or as affecting the output of the motor. They will be confined to the stator teeth, and are therefore very easily got rid of. The scheme of connecting the windings in two or more circuits as suggested by the last speaker is frequently met with, but is not practicable in many cases, particularly in high-tension motors. With regard to the question of bearings, I should like to endorse Mr. Miles Walker's views that on good bearings the wear should be practically nil. If bearings start to wear quickly, it is generally necessary to alter the mechanical arrangements, or instal larger bearings. The wearing is mostly due to bad lubrication, or some mechanical feature.

Mr. Lawson. Mr. F. A. LAWSON (*communicated*): I have been very much interested in the oscillograms of the E.M.F.'s induced in search coils placed in the stator slots, but note that these records have been taken only on light load. The following remarks on some experiments carried out at the Applied Electricity Laboratories, Liverpool University, by myself some time back, may be of interest as showing the effect of load on the field variations. The machine used for the experiments was a 2-phase 4-pole 5-B.H.P. motor which was run on a 200-volt 50-cycle supply circuit. The stator slots numbered 48 and the rotor 36; search coils were fitted in positions shown in Fig. A. Coils 2, 3, and 4 spanned a pole-pitch and consisted of one turn. Coil 1 consisted of five turns wrapped round the tip of a tooth as shown. The wave shape of the induced E.M.F. in coil 1 for light load is shown in Fig. B, and consists of a fundamental due to the main field and a number of ripples corresponding to the number of rotor teeth passing the coil per second. The amplitude of the ripples varies according to the strength of the field in the tooth. By inserting a slip resistance in the rotor circuit the speed of the rotor was reduced, and, as shown in

Fig. C, the number of ripples corresponding to one wave-length of the fundamental is reduced from about 18 to 16. Fig. D shows the induced **Mr. Lawson.**

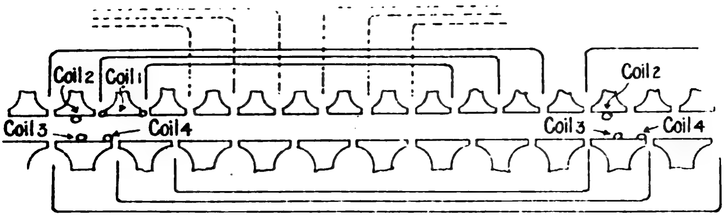


FIG. A.—Position of Coils.

E.M.F. on load, and it will be seen that the pulsations have increased greatly in amplitude. The shape of the wave-form suggests that there

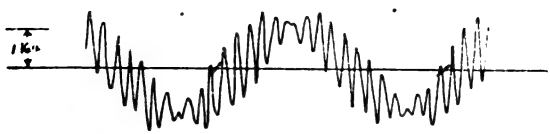


FIG. B.—Coil 1, Light Load.

are two sets of pulsations superposed—those due to the main field and those due to stray flux caused by the stator and rotor currents. The

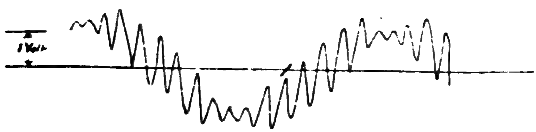


FIG. C.—Coil 1, Light Load, Slip Resistance Inserted.

main point, however, seems to be that on load the losses due to the high-frequency E.M.F.'s induced in stator and rotor teeth will be

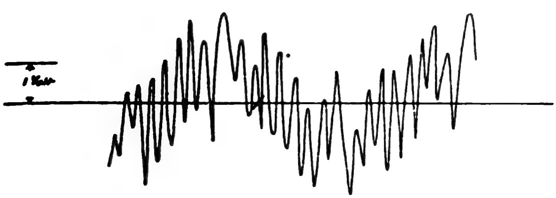


FIG. D.—Coil 1, Full Load.

considerably greater than those on light load, which latter can be experimentally determined. Fig. E shows the E.M.F. induced in coil 2 on light load, and Fig. F the same on full load; the ripples in the E.M.F.

Mr. Lawson. wave are very pronounced on load, absorbing part of the applied potential difference and reducing the strength of the main field. It will be noticed that the main field in Fig. F seems to change in shape. It was found that a complete cycle corresponded to a slip of one-sixth of a revolution, *i.e.*, when the rotor coils are again in the same position relatively to the revolving field. It would not be possible to show how this wave varies during a slip of 1 revolution; but, briefly stated, the fourth harmonic moves slightly from one side to the other of the zero line and also increases and decreases in magnitude slightly. On light

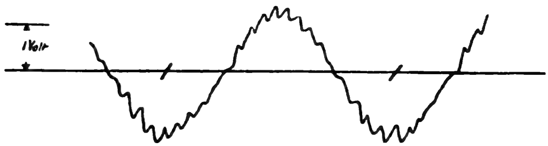


FIG. E.—Coil 2, Light Load.

load, however, there is a curious difference; the amplitude of what we may call the fourth harmonic varies, increasing to a maximum and sinking to zero, then increasing to a negative maximum. It would appear that on light load a true fourth harmonic is produced by the actual change in magnitude of the main flux when the currents in the two phases are equal, as opposed to the moment when one is a maximum and the other zero. On the other hand, on load we have superposed in the rotor two E.M.F.'s due, one to a third harmonic of

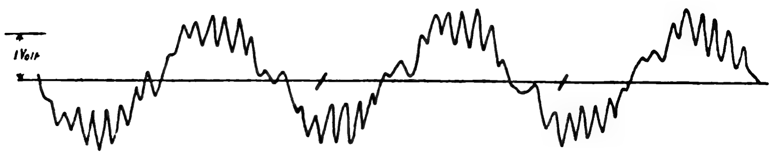


FIG. F.—Coil 2, Full Load.

the main field rotating in the opposite direction to that field and with one-third of its velocity, and the other due to the fifth harmonic of the main field which rotates in the same direction but with a fifth of its velocity. The actual rotor current does not show these pulsations to the extent that might be expected owing, as Mr. Smith remarks, to the coil distribution and the partial cancelling out of the different pulsations. One is led to inquire what the effect of these irregularities of the field is on the working of the machine as regards torque. In the case of polyphase motors when running the effect of the field harmonics will be slight. Their effect, however, will be more marked on starting, especially in the case of squirrel-cage machines. When, for instance, the machine has nearly, in the case of the 2-phase motor considered,

attained one-ninth of its synchronous speed, it is being driven partly by that field which revolves at one-ninth of the speed of the fundamental. As it passes through the speed corresponding to the synchronous speed of this field, the driving action becomes a braking action, and the motor may even start to "crawl"—that is, not to increase in speed. This action has been already noticed by Kloss and others, and Arnold goes into the matter in his Vol. V. i., "Die Wechselstromtechnik." With a view to determining how the starting torque of the motor varied with the position of the rotor on switching-on the following arrangement was made. A varnished mahogany disc was fitted on to the rotor shaft, the disc being about 15 in. in diameter; 48 steel contact-pieces of clock spring were driven into saw cuts made in the disc at equal distances round the circumference, adjustment to within 1 per cent. being made by filing. Another steel spring was placed just above the disc so that contact could be made by each of the 48 contact-pieces through an external circuit battery and one set of oscillograph strips and back through the motor shaft to the contacts. By this arrangement on switching on the motor a battery was short-circuited through a resistance across the oscillograph strip, which strip at the same time was connected to the stator leads to give the potential-difference wave of the motor. As the motor started up a series of sharp deflections from the potential-difference wave showed when the rotor moved each successive 48th of a revolution. This device proved very successful, and by means of the records obtained, time-space, time-speed, and finally torque curves could be obtained, the moment of inertia of the rotor being known. The oscillograph drum was utilised, by means of a specially arranged tripping switch, to start the motor up just before the record was taken and a contact-making device was fitted to the supply generator and inserted in the above circuit, so that the supply potential difference could be switched on at any point on the potential-difference wave. The records were taken for the case in which the resistance inserted in the rotor was sufficient to cause it to start up with about twice full-load torque. The motor started up almost immediately after switching on, and for different positions relatively to the stator there were differences up to 30 per cent. in the value of the torque on starting. The torque also varied according to the point of the E.M.F. wave at which the motor was switched on. The rush of current on switching-on was clearly shown by a displacement to one side of the zero line of the current wave, and a record of the rotor current in one rotor phase showed also clearly the change in wave shape of the current according to the position of the rotor relatively to the stator. This change is probably due to the effect of the change in the total field of the motor alluded to earlier. Mr. Lawson.

Mr. C. F. Smith (*in reply*): Mr. Cramp takes exception to the statement that it was to be expected that the voltage measured at the terminals of several stator search-coils connected in series should agree with the arithmetic sum of the voltages of the coils as measured Mr. Smith.

Mr. Smith. individually, except when fairly low tooth densities are employed. Although I must admit that, with saturated teeth, the phase of the fluxes in different teeth acted upon by a given magnetising current will not be identical, I still maintain that the statement in the paper is accurate, inasmuch as any phase displacement which could occur with any reasonable degree of saturation, would be entirely inadequate to produce a measurable effect on the virtual voltage of the grouped coils. I cannot agree with Mr. Cramp when he says that the maximum pulsation produced in an otherwise stationary field by the rotation of the rotor teeth will not necessarily take place where the flux itself is a maximum. Pulsations due to other causes, such as the variation of the field itself, may have a greater amplitude at other points, but these are shown to be of relatively small amplitude. The next point to which Mr. Cramp alludes is the variation in total flux per pole, due to the varying reluctance of the air-gap as the teeth of the rotor come opposite to those of the stator. This variation, as he points out, depends on the value of the G.C.F. of the two numbers of teeth per pole. He does not, however, notice that the pulsations arising in this way will have a periodicity differing from that of the tooth pulsations shown on the oscillograms in the paper, so that they would be clearly distinguished from them. In my motor, there were 15 slots per pole of the stator and 12 slots per pole of the rotor. In one particular position of the rotor there will thus be three rotor teeth exactly opposite to the same number of stator teeth, when we may assume that there will be a maximum value of the total flux. At the same instant there are three rotor teeth which are only one-fifth of the breadth of a rotor tooth from direct opposition to three other stator teeth. It follows that the frequency of the flux pulsations to which Mr. Cramp alludes will be five times that due to the flux pulsations shown on the curves in the paper and in Mr. Lawson's results. Probably this high periodicity would not have been well recorded by the oscillograph employed ; but I think the fact that there is no indication of such variations, shows that they are very small in amplitude. In this connection I may mention that the voltages induced in the coils on the second motor experimented upon did not show any decided proportionate decrease in magnitude, as suggested by Mr. Cramp, but were such as fully bore out the calculated values worked on the lines indicated in the Appendix to the paper. In regard to the effect of unevenness of the air-gap, I think that the later curves in the paper give a good idea of its effect in modifying the total flux of the poles. The more important effects of such unevenness on the losses in the motor form a subject on which further experiments are now in progress, and on which I hope shortly to have further communications to make.

In reply to Professor Marchant, I have ventured in my observations on Mr. Lawson's communication to express the opinion that his curves are hardly sufficient evidence of a very large increase in the pulsation losses caused by a load on an induction motor. The "magnetic drag" on the rotor, due to its eccentricity, will be mainly in a direction

perpendicular to the axis of the shaft. I think Professor Marchant has misunderstood what is perhaps rather an unfortunate term, as representing a tangential drag, instead of a radial one. Mr. Smith.

I think that the two sets of pulsations referred to by Mr. Worrall are the same as those that I have referred to in my reply to Mr. Cramp, although I do not quite follow Mr. Worrall's statement that the pulsations due to the rotor teeth are of much less import under the usual conditions of working.

Dr. Rosenberg's contention that the unsymmetrical rotor currents due to an eccentricity of the rotor can never reach a considerable value is an important one, in connection with the losses to be expected from this cause. I think that this is a point on which further experiment would be of value, and I hope to be able to furnish some experimental data before long.

Mr. Frith's suggestion for connecting the stator windings in parallel instead of in series would, of course, produce a more even distribution of the flux round the air-gap, although I believe that practical difficulties in winding do not make this plan a desirable one for general adoption.

I think that Mr. Aldous rather begs the question in saying that any increase in losses due to the rotor eccentricity must be unimportant.

I wish to thank Mr. Lawson for his contribution to the discussion; his curves are of great interest. As he observes, the oscillograms given in the paper were all taken at synchronous speed, and therefore without load on the motor. The tests were not, however, confined to these conditions, and my own observations as to the effect of load on the amplitude of the tooth pulsations are not in agreement with the conclusions which Mr. Lawson derives from his curves. Although my results show the existence of pulsations in the stator teeth having about the same relative magnitude as those found by Mr. Lawson, I have always found a decrease in these oscillations under load and a maximum value at synchronism. Thus, the virtual voltages of coil j wound round a single tooth of the stator were observed to have the following values:—

With rotor stationary	2·84
With rotor running under load	3·90
With rotor running synchronously	5·24

I think that these results are in accordance with ordinary experience of inductive circuits in which an increase of current has the effect of damping out high-frequency magnetic oscillations. I would suggest that possibly the increased amplitude of the oscillations under load observed by Mr. Lawson were due to the position of his search-coil on the tooth, and that the voltages obtained were not such as to represent the actual pulsations of the flux in the tooth itself, but rather the vibrations of an unstable leakage field, possibly not affecting the actual tooth induction to any great extent. This suggestion seems to be partly borne out by Mr. Lawson's own description of the curves,

Mr. Smith.

and also by the fact that his coil appears to be situated considerably nearer to the tip of the tooth than mine. Without further confirmation, I venture, therefore, to doubt his conclusion that the losses due to the flux pulsations increase considerably with the load on the motor. Mr. Lawson's further experiments are also interesting; the variation in starting torque is certainly connected with the irregularities of the field, but is affected more by the G.C.F. of the number of stator and rotor teeth than by the actual number of the latter. A motor which showed positions where starting was difficult would not necessarily show unduly high pulsations in the flux per tooth.

INHERENT SPEED REGULATION OF THE DIRECT-CURRENT SHUNT MOTOR.

By E. W. SHORT, Associate Member.

(*Paper received April* 28, 1910.)

It is customary to consider the direct-current shunt motor as a machine which runs at constant speed when supplied at constant terminal voltage, and of which the steady speed may be varied only by the use of a regulating resistance in the shunt field circuit. That this assumption is not strictly correct, and sometimes not even approximately true, was brought to the author's notice some time ago in the course of testing a number of direct-current shunt motors driving textile machinery. The speed of the motors tested was nominally constant within 1 or 2 per cent., but on account of the intermittent nature of the load on the motors, though they were not overloaded, the actual speeds showed very considerable variation from constant value.

GENERAL EFFECT OF A VARYING LOAD.

To summarise briefly the conclusions arrived at as a result of the tests referred to, it appears that although a direct-current shunt motor may be so designed, and its voltage drop and brush position may be so adjusted, that it runs at the same speed on no load and on steady full load, at any given temperature, yet the speed of the same machine will vary very considerably when working on a rapidly varying load such as is often met with in industrial conditions. In short, that tendency of a shunt motor to maintain perfectly even speed under all conditions, which might be called its inherent speed regulation, is sometimes not so good as might be supposed. Even if the motor is differentially compounded for perfect speed regulation for all steady loads within the usual limits of output of the machine, or if interpoles are added to allow greater latitude in the brush position or in the working range of the flux, the particular correction which is adopted disappears when the motor is worked on a rapidly varying or intermittent load, and the speed variation may be of considerable importance.

The speed curves reproduced in Fig. 1 were obtained as the result of tests taken at various times on three different shafts in textile factories driven by direct-current motors. These records were

obtained directly by means of a Moul recording tachograph, a pulley on the instrument being driven by a light belt of linen tape from a convenient pulley on the shaft under test. The full range covered by any one record is a speed variation of 12 per cent. above or below a mean average speed; the distance between the thin lines represents a speed change of 1 per cent., and between the thick lines a change of 5 per cent. The speed of travel of the paper can be varied at will from 1 millimetre per second to 20 millimetres per second, as required.

Curve A records the speed of the main shaft in a weaving shed, this shaft being belt-driven from a 10-H.P. motor. The load torque

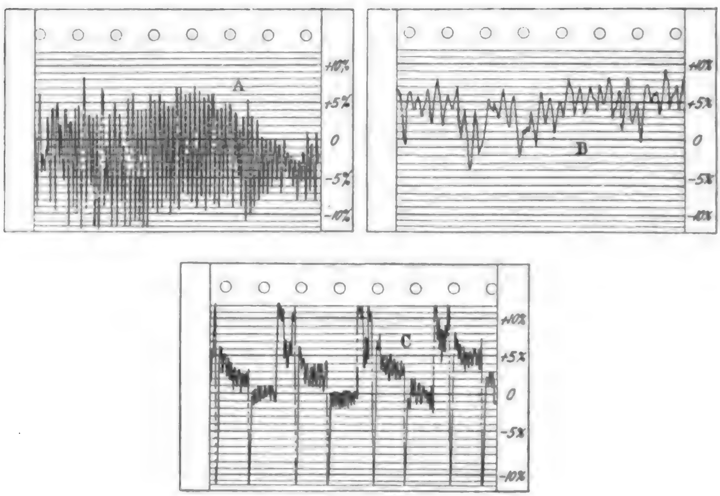


FIG. 1.

on the shaft of a weaving shed is extremely variable, because the action of a single loom is oscillatory, and the power required to drive it is intermittent, and because a number of looms often fall into step with each other, and all require the maximum driving torque at the same moment. A load approaching full load may thus be thrown on and off the driving motor from 60 to 200 times per minute. The effect on the speed is apparent in record A, the length of which corresponds to a period of 15 seconds. At a point near the end of the record, near the right-hand side of the Fig., the looms are out of step, so that the load on the motor is fairly steady, and the total speed variation is only about 3 per cent., while a few seconds earlier the load varies in a periodic manner and the speed varies widely, the maximum variation reaching about 18 per cent. It was impossible to test the speed of the motor shaft itself, but this large and regular

variation of the speed of the driven shaft cannot be attributed either to belt slippage or to belt swinging, but is entirely due to the bad speed regulation of the motor. It should be added that the motor was a plain shunt-wound machine and not specially designed for constant speed.

Curve B is somewhat similar to curve A, and was obtained from another weaving-shed shaft driven by a 20-H.P. shunt motor. This curve is on an extended scale, the length of the record representing a period of about 7½ seconds. The total speed variation is not so large as in the case of curve A, but the character of the speed changes is more clearly seen.

Curve C records the speed variation of a countershaft in one of the spinning-rooms of a textile mill. This countershaft was driven by an 8-H.P. 115-volt direct-current shunt motor, and one spinning mule was driven from the countershaft. The whole record corresponds to an elapsed time of 1¼ minutes. In this case the motor was subjected to sudden periodic fluctuations in load, and the vertical lines dropping to the bottom of the record represent belt slippage, due to the inability of the motor torque to respond immediately to the load changes. On a sudden load coming on, the motor dropped in speed, causing the belts to slip immediately the motor again attempted to pick up speed on the dead load.

In each of the drives to which these curves relate, the results obtained by the employment of the electrical drive were unsatisfactory from the textile point of view. The discrepancies between the actual results obtained from the drive and those which it was reasonable to expect could be obtained, were both important in amount and serious in their consequences; neither the amount nor the quality of the work produced on the textile machines was as good as would have been obtained by driving at constant speed. Since textile machines are arranged throughout a mill to follow each other in regular sequence, any decrease in the production of one set of machines affects adversely the output of the whole mill. Moreover, the same textile machine will spin or weave an even and uniform yarn or cloth, as the case may be, when driven at a steady speed, but will produce only an uneven and inferior product when the speed of the drive is variable, and this fact is of immense importance to the manufacturer when putting his goods on the market.

Having indicated the disadvantageous results which sometimes occur in the textile industry, and which may be equally disadvantageous under similar circumstances in any other industrial application of the direct-current shunt motor, it is proposed to show that the observed behaviour of such a machine on a rapidly varying load is quite in consonance with theory. This will be illustrated by a specific case, for which the theoretical speed curves will be drawn. Some, at least, of the features of such behaviour do not appear to be widely known, or at any rate have not received any serious attention amongst power engineers and technical writers in this country.

Effects of Change of Load and Temperature.

Before proceeding to consider the effect of variable loading on the speed of a shunt-wound motor, the ordinary speed characteristics of such a machine when working on steady loads may be briefly recapitulated.

The decrease in the speed of a shunt motor running light, when full load is put on, is quite obvious. If the motor is supplied at

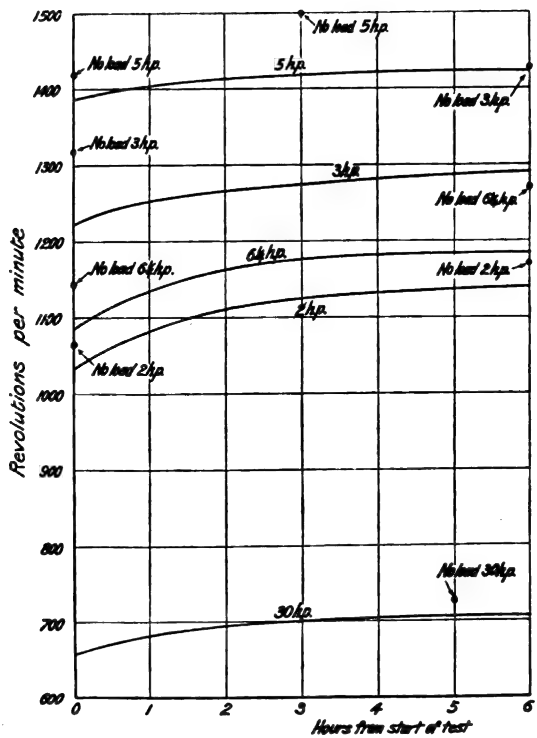


Fig. 2.

constant terminal voltage and the flux is constant, the speed is directly proportional to the back E.M.F., and the latter decreases at full load, due to the voltage drop in the resistance of the armature winding and the brushes. Thus, if the total voltage drop is 5 per cent. of the terminal voltage of the machine, then the steady speed at full load will be 5 per cent. lower than the no-load speed, the temperature of the shunt windings remaining unaltered, and the brushes being in the neutral position.

The ordinary increase in the steady full-load speed of a shunt-

wound motor due to the rise in temperature of the shunt field coils is also well known. During a run of a few hours on load the shunt field winding gets warm, and as its resistance increases, the voltage at the terminals of the shunt windings being constant, the excitation decreases and the speed of the motor rises. The effect is shown very clearly by the test curves in Fig. 2. The Fig. includes the results of tests on five direct-current shunt motors, of which the rated outputs vary from 2 H.P. to 30 H.P. The readings of speeds from which the curves are constructed were obtained, not by the author, but during the ordinary manufacturing works tests for the temperature rise of each machine after a 6 hours' run, taken in the usual way. The alteration of steady full-load speed, from that corresponding to the cold condition of the windings at the commencement of the test, to that for full temperature rise after a 6 hours' run, shows an increase of 10·2 per cent. in the case of the 2-H.P. motor running at 1,140 revs. per minute, and an increase of 7·1 per cent., for the 30-H.P. motor running at 705 revs. per minute. The minimum speed variation from cold to hot condition is 2·5 per cent. in the case of the 5-H.P. motor running at 1,420 revs. per minute. The isolated points indicate the steady no-load speeds observed when the load was taken off for the purpose of making observations at various times during the tests.

This tendency for the steady full-load speed of direct-current shunt motors to rise when the shunt field coils warm up may be minimised by designing the shunt field coils of the motor liberally, so that the magnetic circuit of the machine is worked at a point well above the knee of the saturation curve, and the change in flux for a given change in the exciting current is a minimum. At the same time, the temperature rise of the field coils should be kept as low as possible.

The speed variation due to change of temperature may be corrected by the use of a regulating resistance in the field circuit of each motor. If the regulating resistance is cut out as the shunt winding grows warm, the exciting current may be maintained constant and therefore the speed kept constant also. In practice this would involve continual supervision of all the constant-speed motors in any given plant, especially if the load on certain machines were to vary from hour to hour, causing the temperature of the windings to vary also to some extent. It would also be necessary to provide a tachometer or similar device to indicate the speed of each motor or driven shaft. As a last resort, in the case of especially important drives requiring large motors some kind of automatic governor and regulator might be employed, to cut resistance out of the shunt field circuit, when the speed begins to rise and to re-insert it when the speed falls below the normal speed at which the motor is required to run.

Influence of Brush Position.

The steady full-load speed of a direct-current shunt motor depends also upon the position of the brushes on the commutator. In general,

rocking the brushes backwards, contrary to the direction of rotation of the armature, causes the speed to increase, and rocking them forward causes the speed to decrease.

The action will be clear on reference to Fig. 3. The armature cross ampere-turns are set up by the armature conductors which lie under the pole-faces N, S, but there is no demagnetising action at all while the brushes are in the neutral position. When the brushes are rocked backwards, however, to *a* and *d*, the effect of the back ampere-turns due to the belt of conductors included between *a b* and *c d* is entirely demagnetising, and the total flux of the machine is reduced when the armature conductors carry current. Were the brushes rocked forward from the midway neutral position, the current in the same belt of conductors would be reversed and the ampere-turns due to these conductors would then be magnetising ampere-turns, causing a drop in speed at full load.

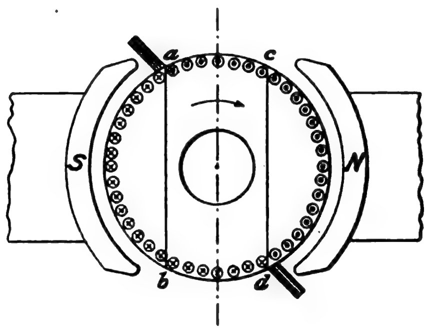


FIG. 3.

The action of the armature cross ampere-turns on load is to shift the position of the neutral zone of the field backwards and consequently the best non-sparking position for the brushes is usually more or less backwards from the neutral position, while shifting the brushes forwards causes sparking, because the armature coils would be cutting a strong field under the forward pole horn while they were under commutation.

The important point to note is that rocking back the brushes from the neutral position causes the full-load speed to rise, thus making available for non-reversing motors a means whereby the decrease in speed on load due to voltage drop may be offset, and the steady speed maintained approximately the same at no load, full load, and intermediate loads. A large backward lead will cause the speed to rise from no load to full load. Plain shunt-wound motors, therefore, have the best steady speed regulation when the brushes are rocked just so far backwards from the neutral position that the rise in speed due to the armature back ampere-turns balances the drop in speed due to the effects of the armature voltage drop. With a view to obtaining the closest speed

regulation when using shunt motors, even on steady loads, it is of great importance to adjust the position of the brushes carefully, not only with reference to the non-sparking position but also with reference to the speed. Otherwise, undue speed variation will take place, even on slowly varying loads. If interpoles are used, sparkless commutation may be definitely secured when the brushes are adjusted solely with reference to obtaining the best speed regulation.

Differential Compounding.

If sufficient backward lead cannot be given to the brushes to obtain the same steady speed from no load to full load, or if it is necessary to keep the brushes in the neutral position for reversing or for other special reasons, a differentially compounded field may be employed. In this case the shunt field coils must be designed to provide the full ampere-turns necessary to set up the maximum flux, which is at no load. Instead of rocking the brushes and utilising the demagnetising effect of the armature back ampere-turns to reduce the flux at full load, the brushes can be kept in the neutral position and the series coils designed to provide sufficient demagnetising ampere-turns, when full-load current flows, to reduce the flux, the amount of reduction being proportional to the difference between the back E.M.F.'s at no load and full load. The series winding must usually be cut out of circuit, of course, when starting the motor.

Effect of Mutual Inductance.

Although any given motor may be arranged, however, by rocking the brushes or by differential compounding, to regulate perfectly on slowly varying loads, quite other effects show themselves, as already stated, when the load is quickly intermittent or rapidly varying. This is due to the mutual induction between the shunt and series field windings, or between the armature and shunt field windings. Since there must be a change in flux between no load and full load, if the motor is to run at the same steady speed, and since any change in the flux in the armature and poles can only take place slowly, on account of the self-induction of the shunt field winding, it follows that a certain delay occurs in the final adjustment of the motor speed when the load it is called on to develop suddenly changes. The demagnetising action of the armature back ampere-turns or of the series field coils cannot immediately take effect, and in the interval the speed of the machine varies as though there were no special correction provided.

When series and shunt windings are wound on the same pole, the direct effect of the mutual inductance existing between the two sets of coils is that any change in the current in the series coil either tends to produce a momentary current in the shunt coil, if no current flows in

the latter to begin with, or affects momentarily any current which may already be flowing in the shunt circuit. Following the usual effect of mutual inductance, the direction of the induced current round the pole is opposite to the direction of the inducing current if the latter is increasing, or in the original direction of the inducing current if the latter is decreasing. If the induced current in the shunt coils is superimposed on an existing current, the effect of the induced change in the value of the current is opposite to the effect of any change in the value of the current in the series coils. If the coils are wound in the same sense, and the series turns are magnetising, as indicated in Fig. 4, then, as the series current increases, any existing shunt current will be temporarily reduced. If the series coils are demagnetising in action, as in the case of the differentially compound motor, the shunt current is momentarily increased when full-load current begins to flow in the series turns.

From the foregoing statements, it follows that the magnetising or

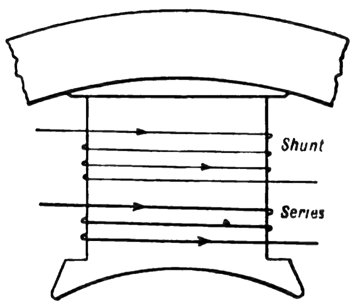


FIG. 4.

demagnetising effect of a compound winding is not effective immediately the series current flows, since any change in the series ampere-turns is accompanied by a momentary change in the shunt ampere-turns, in the opposite direction, so that for the moment the total of the effective ampere-turns acting on the pole is unaltered, and the flux is also unchanged. The change in the flux takes place comparatively slowly, simultaneously with the return of the shunt exciting current to its normal steady value. The rate at which this change takes place depends upon the self-induction of the shunt coils alone, and the return of the shunt current and the flux to steady values takes an appreciable time.

In the case of the differentially compound motor, when full load comes on, the flux in the poles is not immediately reduced to suit full-load conditions, and if the duration of the transient conditions is sufficiently long, the speed of the motor will have time to drop con-

siderably before the flux has attained its steady value. The contrary effect takes place when full-load current goes off the motor; the shunt current is momentarily reduced, thus preventing the flux from increasing immediately and allowing the speed of the machine to rise above normal steady value. If variations in load are rapid and succeed each other quickly, the speed may vary constantly up and down as the load decreases and increases.

If the motor is not differentially compounded, but the regulation depends on the demagnetising action of the armature back ampere-turns, the effects will be practically the same. Any variation of the armature current will cause a momentary and contrary change in the

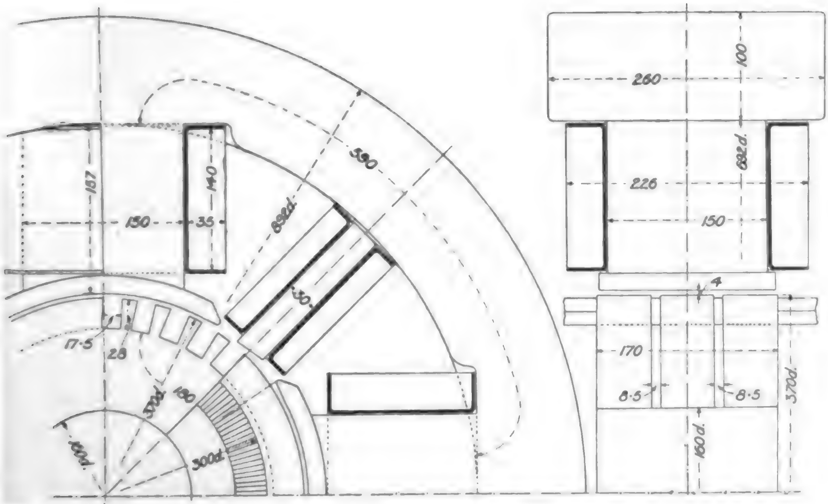


FIG. 5.

shunt exciting current, and the speed of the machine will usually have time to vary up or down before the exciting current and flux have time to settle down to steady conditions.

General Dimensions of 35-H.P. Shunt Motor.

In order to illustrate the foregoing remarks and to develop a specific case of the characteristic behaviour of a direct-current motor on steady and on quickly varying loads, the author has calculated windings and has worked out their properties for a 4-pole motor rated at 35-H.P. 66 amperes 440 volts 750 revs. per minute. The outline dimensions are shown in Fig. 5, and other electrical and magnetic data are as follows :—

Armature.

Number of slots	37.
Wires per slot	5 × 4.
Type of winding	Simplex wave.
Number of paths between brushes ...	2.
Total number of face conductors... ...	740.
Number of commutator segments ...	185.
Resistance of winding (hot)	0·195 ohm.
Volts drop in armature winding and brushes	15.
Armature flux at no load and 750 r.p.m....	$2{\cdot}38 \times 10^5$.
Armature flux at full load and 750 r.p.m...	$2{\cdot}3 \times 10^5$.
Armature ampere-turns per pair of poles	6,000.
Pole-arc/pole-pitch	0·75.

Shunt Field Winding.

Turns per coil	4,850.
Diameter of wire, bare	0·8 mm.
Cross-sectional area of wire	0·592 sq. mm.
Resistance of shunt winding (hot) ...	464 ohms.
Exciting current	0·95 ampere.
Ampere-turns provided per pair of poles	9,200.

Speed Regulation of 35-H.P. Motor on Steady Loads.

The curves in Figs. 6, 7, and 8 respectively show the saturation curve, the variation of no-load and steady full-load speeds with change of temperature of the shunt field winding, and the variation of steady full-load speed with change in brush position.

The calculation of the resistance of the shunt coils corresponding to various temperatures from 0° C. to 60° C. is based on the temperature coefficient for copper of the Engineering Standards Committee: viz., a change in resistance of 0·428 per cent. per 1° C. The increase in the resistance of the motor shunt field coils, due to a temperature rise of 40° C., from 15° C. cold to 55° C. hot, is 16·1 per cent. The no-load speed for the same temperature range increases from 732 to 761 revs. per minute, or 4·0 per cent. of the initial speed, and the steady full-load speed increases from 707 to 734 revs. per minute, or 3·8 per cent. of the initial speed, when the brushes are in the neutral position.

The speed-temperature curves in Fig. 7 may be reduced to the same form as the test curves in Fig. 2 if the rate of rise of temperature of the field coils is known. If the radiating surface of the coils and the watts lost in them are proportioned so as to give a certain final temperature rise, ascertained from tests on similar machines, the

variation of the temperature of the coils with time may be determined approximately from the equation—

$$T = B\left(1 - e^{-\frac{Wt}{BC}}\right);$$

where—

T = temperature rise at any time t, C°.
B = final steady temperature rise, C°.
W = B.Th.U. dissipated in coils per hour = 3412 × B.O.T. units per hour.
t = time from start in hours.
C = calorific value = B.Th.U. required to raise temperature of coils 1°C.

The above formula gives a sufficiently near estimate of the probable time of heating up of the field coils. With regard to the term C., it

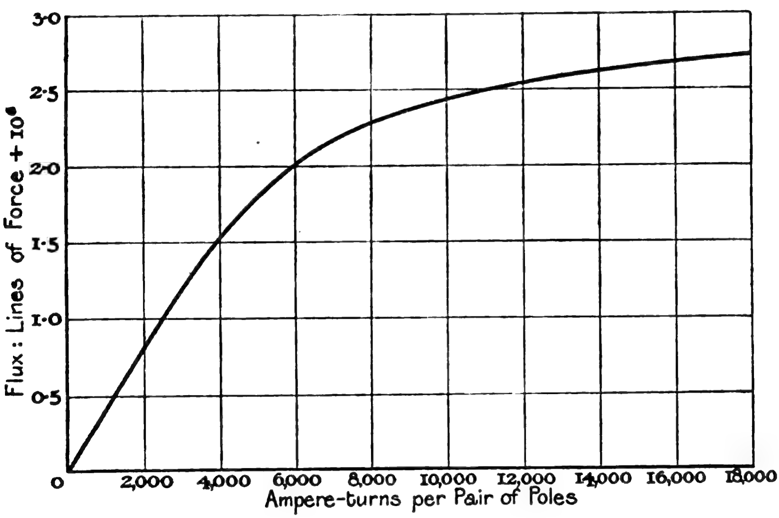


FIG. 6.

would usually be safe to evaluate it as the number of B.Th.U. required to heat both the field copper and the pole limbs through 1° C. If the heat conduction from the coils to the poles is especially poor, due to the method of insulating the coils, it would be safer to estimate on the calorific value of the copper alone.

In constructing the curves in Fig. 8 connecting speed and brush position for this motor, it is assumed that only the armature back ampere-turns, and not the cross ampere-turns, are effective in reducing the flux at full load. The back ampere-turns are simply

proportional to the load and to the amount of shifting of the brushes, thus:—

Demagnetising ampere-turns per pair of poles

$$= \frac{4 \times \left\{ \begin{array}{c} \text{Number of segments back-} \\ \text{ward lead of brushes} \end{array} \right\} \times \left\{ \begin{array}{c} \text{Armature} \\ \text{ampere-turns} \end{array} \right.}{\text{Number of commutator segments per pair of poles}}$$

In this instance the number of commutator segments per pair of

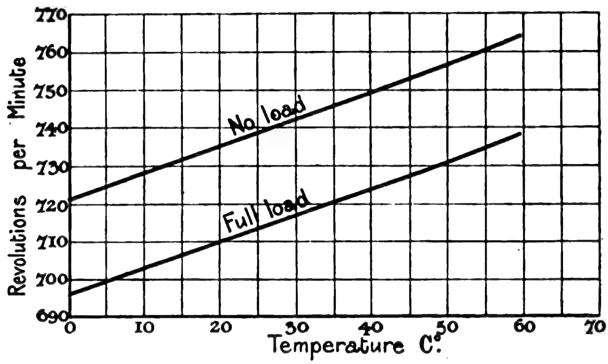


FIG. 7.

poles is $\frac{185}{2} = 92{\cdot}5$, and the demagnetising ampere-turns per pair of poles and per 1 segment of backward lead of the brushes are therefore $\frac{4 \times 1 \times 6000}{92{\cdot}5} = 260$ ampere-turns. The total demagnetising ampere-

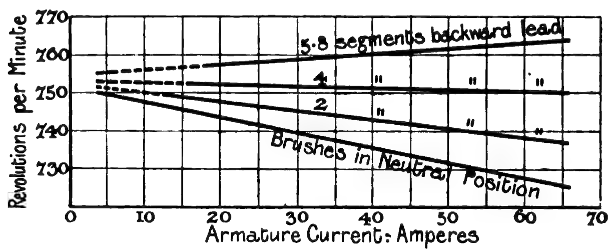


FIG. 8.

turns are found for various brush positions in this way, and by deducting the number of ampere-turns obtained in each case from the total ampere-turns per pair of poles provided by the shunt winding the effective ampere-turns per pair of poles is arrived at. The respective values of the flux are read off from the saturation curve, and the corresponding speeds calculated.

The curves show that if the brushes are in the neutral position the speed drops from 750 revs. per minute at no load to 725 revs. per minute at steady full load, or a decrease of 3·3 per cent. on the rated speed. The brush position corresponding to a steady full-load speed of 750 revs. per minute is 4 segments backwards from the geometric neutral position. If the brushes were given a backward lead of 5·8 segments from the neutral position, corrresponding to a point opposite the trailing pole-tip, the steady full-load speed would be 764 revs. per minute, or a rise of nearly 2 per cent. above normal rated speed. Since the neutral region is usually much narrower, even at no load, than the distance between the pole-tips, the no-load speed will vary slightly with changes in the brush position, and will be higher with the brushes moved back than when they are in the neutral position. In practice the exact no-load speeds obtained when the brushes are rocked back from the neutral position, and also the maximum possible amount of backward movement that can be given to the brushes at full load, will depend to some extent on the exact shape of the pole-horns and on the distribution of the magnetic field between them. In the case of a motor without interpoles, sparking would usually occur at no load with much less backward lead than is possible at full load, owing to the armature coils being subjected to short circuit through a brush while they are moving in a field of definite polarity, and are generating an E.M.F.

Transient Conditions for 35-H.P. Motor.

The behaviour of the 35-H.P. motor on a rapidly varying load may now be considered; in calculating the mutual inductance of the motor windings the author has followed the method applied by C. P. Steinmetz* to the conditions existing in a compound generator.

If the motor is plain shunt wound, and the brushes are kept in the neutral position, the effect of varying load is that the speed simply varies with the back E.M.F. the motor is called on to develop. Since the flux remains constant, if the voltage drop in the motor windings is 5 per cent., the back E.M.F. will be 5 per cent. lower at full load than at no load, and the speed will drop 5 per cent. when full load comes on, if the terminal voltage at the motor is constant. If the terminal voltage drops a further 5 per cent., quite a usual figure to allow in these cases, the speed of the motor will be 10 per cent. lower on full load than on no load.

Instead of showing the effect of variable load on the speed of the motor under consideration under the worst conditions, it will be of considerably greater interest to consider the best results that can possibly be obtained. In the first place, full correction must be made to obtain as good speed regulation as possible on steady load, either by giving the brushes a backward lead of four segments from the neutral position, as already stated, or by differentially compounding the motor

* "Theory and Calculation of Transient Electric Phenomena and Oscillations," p. 141.

field. Since the brushes can be left in the neutral position if differential compounding is adopted, and the method can be employed equally well for either reversing or non-reversing motors, a suitable differential compound winding will be assumed for the 35-H.P. motor and the succeeding calculations will be based on this arrangement. Interpoles can be added to such motors if desired, and the general effect of adopting them will be referred to at a later point.

For a steady speed of 750 revs. per minute, both at no load and full load, the no-load flux is $2·38 \times 10^6$ lines of force and the full-load flux is $2·3 \times 10^6$ lines. The corresponding ampere-turns per pair of poles are read from the saturation curve, and the demagnetising ampere-turns which must be provided by the series winding are $9{,}200 - 8{,}140 = 1{,}060$ ampere-turns; these can be produced by winding on 8½ series turns per pole. Since the brushes are in the neutral position, no allowance need be made for balancing armature back ampere-turns. The principal data regarding the differentially compound field windings which are assumed for the present purpose, and the interpole winding which would be used for this motor, are as follows:—

Field Coils of 35-H.P. Differentially Compound Motor.

	Series.	Shunt.	Interpoles.
Number of coils ...	4	4	4
Ampere-turns to be provided per pair of poles	1,060	9,200	8,150
Number of turns per coil	8½	5,230	63
Total number of turns...	34	20,920	252
Size of conductor, bare	10 × 4 mm.	21 S.W.G.	20 × 1·5 mm.
Cross-section of conductor, square millimetres	40	0·519	30
Length of mean turn, metres...	0·617	0·627	0·47
Weight of copper, kilogrammes	7·5	61	32
Resistance of winding, ohms	0·0105	505	0·079
Exciting current, amperes	65	0·87	65
Loss in winding, watts	45	380	335

The final, or steady, effect of the demagnetising action of the series winding, when 65 amperes flows through 8½ turns per coil, is to change the flux per pole from $2·38 \times 10^6$ to $2·3 \times 10^6$ lines of force. The length of time required to effect this change, after full load comes on, is governed, firstly, by the time of growth of the series current, during which time the shunt current changes also; and secondly, by the time of return of the shunt current to its normal value. The rate of change of the series current depends on the self-induction of the main circuit,

and the time of return of the shunt current to normal value depends on the self-induction of the shunt field winding alone.

If it is supposed, for the sake of illustration, that the motor is one of a number of motors driven from an evenly compounded generator of, say, 150-k.w. output, the motor armature circuit would include the armature and series field coils of the generator, and the armature and series field coils of the motor itself, and the self-induction of the main circuit through any one motor would be about 0·006 henry. Estimating the resistance of this main circuit at 0·29 ohm, the normal rate of

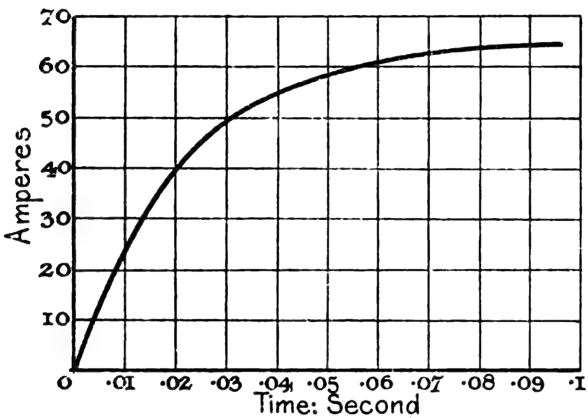


FIG. 9.

growth of the motor armature current when the motor is running and full load is suddenly put on, would be represented by the curve in Fig. 9. This follows the ordinary law for the growth of current in an inductive circuit—

$$C = \frac{E}{R}\left(1 - e^{-\frac{Rt}{L}}\right).$$

The series current reaches 59 amperes in 0·05 second, and 99 per cent. of its final value, or 64·4 amperes, in approximately 0·1 second.

To estimate roughly the momentary change in the shunt current, due to the growth of 65 amperes in the series winding, magnetic leakage between the series and shunt coils may be neglected, and it may be assumed that the values of the inducing and induced currents are inversely proportional to the number of turns in the respective coils, as in the case of the alternating-current transformer. The maximum increase of the shunt current would therefore be—

$$\frac{65 \times 8\frac{1}{2}}{5230} = 0{\cdot}106 \text{ ampere};$$

the actual increase is rather less, or 0·075 ampere, since the initial

change takes a certain time and the shunt current meanwhile tends to return to its steady value. The shunt current increases from its normal value of 0·87 ampere to 0·96 ampere, nearly, in the same time that the main current in the series coils grows from zero to 59 amperes—that is, in 0·05 second.

The natural rate at which the shunt exciting current decreases again from its maximum to the normal value can be estimated as follows: The alteration in the flux per pole which would take place due to a change of 0·106 ampere in the shunt current would be $0{\cdot}06 \times 10^6$ lines of force, and the alteration in the interlinkage of the four shunt coils is $4 \times 5{,}230 \times 0{\cdot}06 \times 10^6 = 1{,}260 \times 10^6$. The increase in interlinkage per 1 ampere change of current at the same rate would be—

$$\frac{1{,}260 \times 10^6}{0{\cdot}106} = 119 \times 10^8,$$

and therefore the inductance of the shunt coils over this range is 119 henrys. The resistance of the shunt coils is 505 ohms. The natural rate of change of the shunt current, when the series current has attained constant value, then follows the law—

$$C = C_0 - (C_0 - C_1)\, e^{-\frac{Rt}{L}},$$

where—

C = current at any time t, in amperes.
C_0 = current at time $t = 0$.
C_1 = final steady value of current.
t = time, in seconds.
R = resistance of circuit, in ohms.
L = self-induction of circuit, in henrys.

The complete cycle of variation of the shunt current is shown by the curve in Fig. 9.

The practical result of the delay in the adjustment of the shunt exciting current to those steady conditions where the effects of voltage drop and differential compounding are balanced, is that the speed must drop to reduce the back E.M.F. and allow full-load current to flow, unless the armature has sufficient flywheel effect to keep the speed at nearly normal value. Since the flywheel effect is usually inadequate to maintain full-load torque for a sufficiently long interval, however, the speed drops, and full-load torque and current only maintained at the lower speed.

The kinetic energy stored by the armature in question, when running at a speed of 750 revs. per minute, is about 7,500 ft.-lbs. If full-load torque were continuously exerted to stop the motor after the power had been cut off it would come to a stop in 0·39 second, after having made only 2½ revolutions. At the same rate, the decrease of speed from 750 to 725 revs. per minute, the speed at which balance

is obtained between flux and back E.M.F., would occupy only 0·013 second. The flywheel effect possessed by the armature when rotating at full speed is thus far too small to be of any practical value in keeping up the speed at the moment load comes on.

If the motor is running at steady speed and full load is suddenly taken off, the opposite cycle of events takes place. When the load torque goes off the motor torque is maintained, because full-load current flows. Since the flux does not increase sufficiently quickly to increase the back E.M.F. and keep the speed steady, full-load current will continue to flow until the speed commences to rise and the motor back E.M.F. is increased sufficiently by this means to check the current. The speed therefore rises quickly, and the sudden

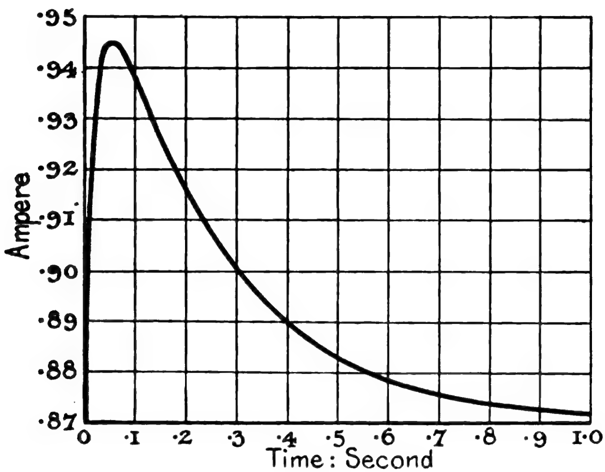


FIG. 10.

decrease of the main current in the series coils now has the effect of causing the shunt current to alter also; the shunt current decreases from 0·87 ampere to 0·795 ampere in 0·05 second, afterwards rising again slowly to its former steady value, completing the cycle of change to within 1 per cent. of its normal value in 0·6 second. At the moment when the shunt current is at its minimum, the value of the series current is about 6 amperes, and rapidly decreasing to zero, the back E.M.F. that must be generated is 438 volts, and the flux is $2·315 \times 10^6$, or not much above full-load value. The speed consequently rises immediately to 770 revs. per minute, and only returns to nearly its normal steady value of 750 revs. per minute in about 1 second, when the shunt current has completed its change, and the flux has increased to its steady value of $2·38 \times 10^6$ lines of force.

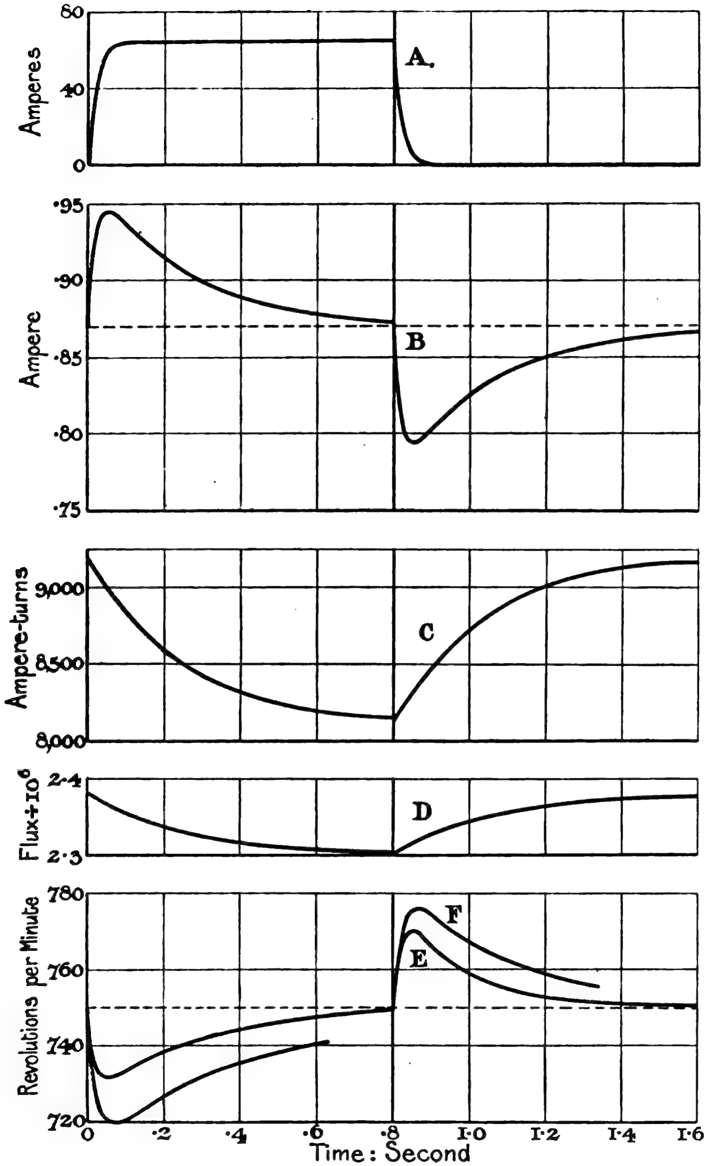
Effect of Rapidly Varying Load.

The curves in Fig. 11 are drawn to show the variation of all the quantities when full load is suddenly put on the 35-H.P. motor, and when it is suddenly removed four-fifths of a second later. Curve A shows the variation of the main armature and series field current, curve B shunt exciting current, C the total effective ampere-turns per pair of poles due to the combined effects of the series and shunt coils, and curve D the consequent variation of the armature flux per pole. Curve E is the speed curve of the differentially compound motor, representing the speed changes when full load is put on and taken off the motor, the latter being supplied at constant voltage.

The effect of running this motor on a rapidly intermittent load is now evident. Every time the load increases from almost no load to full load, the speed drops about 2½ per cent. below normal, and every time full load goes off the speed rises about 2½ per cent. above normal. This assumes that the steady conditions are regained on each occasion before the next alteration in load takes place. If the load is regularly put on and taken off the speed varies up and down about 5 per cent. continuously.

If interpoles are used to ensure sparkless commutation with fixed brushes, the voltage drop in the motor is increased from 15 to 20 volts, so that the full-load flux is only $2 \cdot 27 \times 10^6$ lines, and the main series winding must be increased from 8½ to 10½ turns per coil. The larger interlinkage between flux and shunt turns causes the self-induction of the shunt coils to be increased to 177 henrys. The combined effects on the speed of the increased voltage drop in the motor and the increased inductance of the shunt field winding is shown by curve F, Fig. 11, which represents the speed variation of the interpole machine when full load is first thrown on and then thrown off.

Continuous oscillation of the speed between its extreme values will occur if the machinery driven by the motor offers a periodically varying load torque opposed to the driving effect of the motor. This occurs when driving looms in a textile mill, or a machine tool of which the motion is reciprocating or the cutting intermittent. On such a load, supposing that the duration of maximum current is equal to the duration of no load or minimum load, then the temperature rise of the motor will not be excessive if the maximum current is from 50 per cent. to 100 per cent. greater than the normal current of the motor on continuous rating. The curve in Fig. 12 shows the calculated effect on the speed of the 35-H.P. compound motor of varying the load by different amounts, from a variation of one-quarter full-load current to one and a half times full-load current. The speed change depends upon the amount of the load change, and is not affected materially by the original value of the load, whether this is no load or full load or other value. The speed changes represented by the curve will take place if the motor current varies in response to the load torque by one-quarter, one-half, and three-quarters of full-load current, etc. The



Amperes
80
40
0
A.
Ampere
·95
·90
·85
·80
·75
B
Ampere-turns
9,000
8,500
8,000
C
Flux ÷ 10^6
2·4
2·3
D
Revolutions per Minute
780
760
740
720
F
E
0
·2
·4
·6
·8
1·0
1·2
1·4
1·6
Time: Second

FIG. 11.

respective load changes are assumed to be put-on and taken off at regular intervals of 1 second.

All the foregoing examples of speed changes are based on the assumption that the terminal voltage at the motor remains constant. The curve in Fig. 13 shows the effect if the voltage at the terminals of the differentially compound motor drops 5 per cent. when the motor

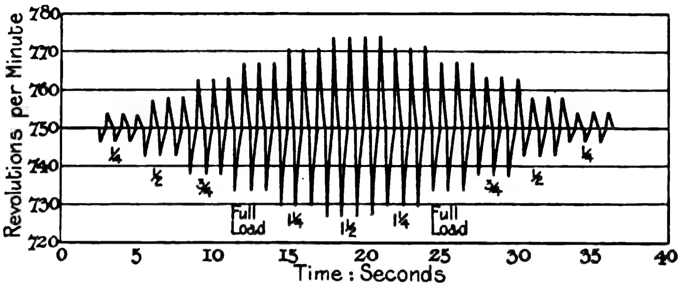


FIG. 12.

takes full-load current. The curve is drawn for load variations of one-quarter, one-half, etc., of full-load current up to a maximum current variation of one and a half times full-load current as before. The maximum speed variation when 50 per cent. overload is thrown on and off the motor is 9·6 per cent. Had the motor been fitted with

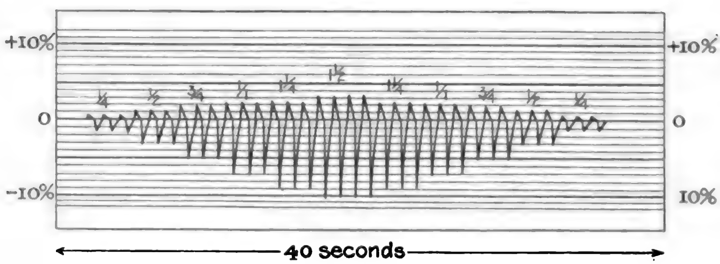


FIG. 13.

interpoles the speed variation would have been very considerably greater. The calculated curves in Figs. 12 and 13 may be compared with the practical records in Fig. 1.

CONCLUSION.

The author's remarks regarding the use of direct-current motors are not to be understood as a condemnation of their use for textile driving as a whole or for driving machine tools and industrial machinery in

general. Nor should the conclusion be drawn that only polyphase induction motors, or even synchronous motors, can be used in order to obtain steady driving on any load whatever. As it happens, the importance of absolutely constant driving speed is more insisted on in the case of textiles than in almost any other branch of electrical power applications, and the majority of electrically driven textile factories happen to be driven by polyphase motors. The main reasons for the general adoption of polyphase driving are probably two in number: First, that the supply authorities in the textile districts mostly supply alternating current; and secondly, on account of the difficulties attributed to the use of the direct-current shunt motor due to the care of the commutator and the variation of speed with temperature changes. This note on the behaviour of the direct-current motor will have served its purpose if it makes clear the real reason why such a machine should not be employed if it is desired to obtain absolutely constant speed when driving a rapidly varying load.

ELECTRIC WINDING.

By G. STJERNBERG.

(*Paper received September* 22, 1910.)

Long before electrical winding was introduced various arrangements were devised to neutralise the influence of the rope weight so as to reduce the torque and consequently the size of the engine. The simplest of all such arrangements, the use of a balance rope gave no satisfactory results in connection with a steam engine. This was due to the uneven torque and the swinging of the rope produced thereby. When electrical winding is adopted this difficulty entirely disappears; the turning moment of an electric motor is absolutely uniform at all speeds, and the impulses which in the case of the steam engine create the swinging of the rope do not exist. The balance rope, therefore, runs quite steadily without any jerks, and there is no necessity at all for any guide pulleys at the bottom of the pit. Such balance ropes are now working in a great number of pits at the highest shaft speeds which have hitherto been adopted. A balance rope is generally taken of the same weight per unit length as the winding rope, but it can of course, if special circumstances make it desirable, be taken either heavier or lighter. When of equal weight the balance rope in no way increases the strain on the winding rope, but it keeps the stress nearly constant at all positions of the cage, and the only variation that occurs is due to the coal weight and the effort required to accelerate the suspended masses. Without a balance rope the maximum stress is exactly the same as with a balance rope, but it varies for each winding operation between the value which corresponds to the weight of the cage alone and the value which corresponds to the weight of the cage, trams, and rope to which must also be added the acceleration effort. The stress on the rope in this case, therefore, varies between very considerable limits.

A winding rope is, therefore, worked with at least the same factor of safety when a balance rope is provided, but this only applies to an electrical winder. In the case of a steam winder the swingings are liable to increase the stress. Taking this into consideration, it is correct to say, at least for depths up to 1,000 yards, that a balance rope can always be used for an electrical winder, and a general discussion on this subject may therefore be based upon the assumption that such a balance rope is used. We shall, therefore, in the following remarks assume that we are dealing with a winder with cylindrical

drum and balance rope, and that in stopping and starting we accelerate and retard at a constant rate, since this is the most favourable arrangement if it is a question of quick winding. The speed diagram then takes the form shown in Fig. 1.

During the time t_a the winder is gradually brought up to full speed V, which remains constant during the time t_c and again during the time t_r, slowly decreasing to zero. It is at once clear that the times t_a, t_c, and t_r can be chosen in any manner we like as long as their sum is equal to T—*i.e.*, to the time allowed for the wind. The corresponding speed diagram must then be such that the area enclosed by it is equal to the depth of shaft S. Innumerable diagrams can be drawn fulfilling these conditions, but they are, of course, not equally favourable. We find that the smaller we take the time t_c the larger will be the maximum shaft speed V, and *vice versâ*. Theoretically the smallest shaft speed would be obtained if t_c is equal to T—*i.e.*, if we can

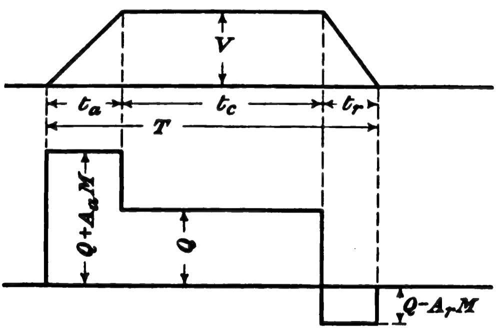


FIG. 1.

suddenly get the winder up to full speed and stop equally suddenly at the end of the wind. The speed diagram would then be represented by a rectangle erected on T, the height of which would be S/T; this is a condition which can be approached in case of ordinary slow-speed lifts. The largest value of the maximum shaft speed V is naturally obtained if t_c is equal to zero—*i.e.*, if the slowing down commences immediately the maximum speed is reached. In this case the speed diagram is represented by a triangle of height 2 S/T. N S/T is the average winding speed. If we now introduce the ratio between the maximum speed and the average speed $r = V/(S/T)$ then it is clear that this value r must always be larger than 1, but cannot be larger than 2. It is of decided advantage to introduce this quantity in the calculations of winding diagrams, as will be seen later on. Each value r gives a definite value for the full-speed period t_c, and consequently for the time available for acceleration and retardation $t_a + t_r = T - t_c$. The time required for the acceleration t_a may be taken equal to retardation t_r, or the ratio between these two times may be varied in any desired

manner. This is occasionally useful, and we will therefore introduce the ratio m between these two times—*i.e.*, $m = t_r/t_a$. If we give definite values to m and r, then the form of the speed diagram is fully determined.

The power diagram is derived from the speed diagram in the usual manner. If Q_1 is the useful load and e_1 the shaft efficiency, then, since the friction is always opposed to the motion of the system, and therefore can be directly added to the useful load, we can by substituting

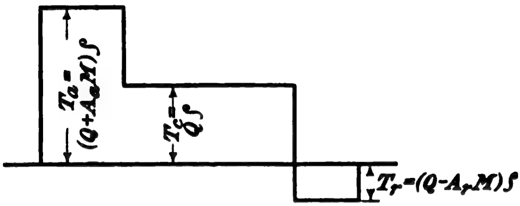


FIG. 2.

for Q_1 the value of $Q = Q_1/e_1$, deal with the winding system exactly as if it were frictionless with a useful load Q. This friction includes not only the friction of the guide ropes and pit-head pulleys and air friction in the shaft, but also the bearing friction of the drum and motor shaft, the windage and the power required to overcome the bending friction

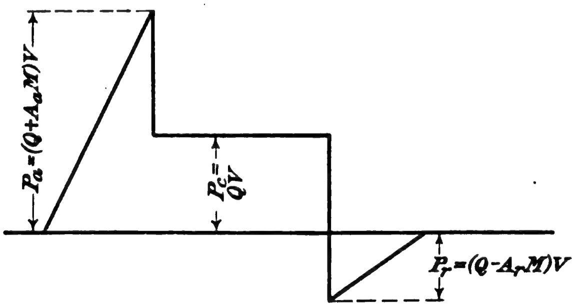


FIG. 3.

of the rope. Where guide ropes are used the shaft efficiency for direct-coupled winders is approximately equal to 0·83; at least this value can be obtained. Where rail guides are used, the friction is more uncertain, and depends very much on the condition of the rails. It is therefore advisable in such cases to take a somewhat lower value for the shaft efficiency. If the motor is geared, the efficiency of the gearing must be taken into account.

In addition to the static load Q, we have to consider the inertia of

the moving system. With a cylindrical drum all the moving parts are moving at proportional speeds, and we can therefore introduce an equivalent mass M which, moving at rope speed, would produce the same effect as all the moving parts of the gear. For cylindrical drums the ratio between the static load Q and the mass M varies somewhat, but between comparatively narrow limits. With a distance between the pit-head pulleys of 5 to 6 ft., M/Q lies between 1·1 and 1·3 (in the metric system). The larger value corresponds to pits of about 500 to 600 yards depth with a useful load of about 3 tons; for shallower pits or larger loads a smaller value can be taken. If instead of cylindrical drums Koepe discs are used, this value may be as low as 0·8. If A_a is the constant acceleration, A_r the constant retardation, then the equivalent pull on the rope during the starting period is equal to $Q + A_a M$; during the period of constant speed it is equal to Q; and during the retardation period it equals $Q - A_r M$, as shown in Fig. 1.

Multiplying these values with the radius ρ of the drum, we get a corresponding torque T_a during the acceleration period, T_c during the full-speed period, and T_r during the retardation period, as shown in Fig. 2.

The corresponding power outputs we obtain by multiplying these values of the rope pull with the corresponding speeds v, as taken from the speed curve (Fig. 3). To enable us to discuss the problem in general we shall now, instead of the torques T_a, T_c, and T_r, introduce the ratios $\frac{T_a}{Q\rho}$, $\frac{T_c}{Q\rho}$, and $\frac{T_r}{Q\rho}$, *i.e.*, the ratio between the torques at the various periods of the wind and the static torque produced by useful load and friction. Similarly we will, instead of power, introduce the ratio (power)/(Q S/T). Q S/T clearly represents the power required to wind the useful load Q at a constant speed equal to the average speed. It is now clear that the winding times t_a, t_r, and t_c can be expressed as a function of T, r, and m, the acceleration and retardation as functions of S/T^2, r, and m, the ratios (torque)/$Q\rho$ and (power)/(Q S/T) as functions of MS/QT^2, r, and m. T, S/T^2, and MS/QT^2 are therefore the only constants which enter into the equations determining the speed, torque, and power diagrams.

Mathematically this result is obtained as follows:—

$$t_a + t_c + t_r = T, \quad \text{or} \quad t_c = T - (t_a + t_r) \quad . \quad . \quad . \quad . \quad (1)$$

Area of speed diagram = S gives—

$$\left(\frac{t_a + t_r}{2} + t_c\right) V = S, \quad \text{or} \quad T - \frac{t_a + t_r}{2} = \frac{S}{V} \quad . \quad . \quad . \quad (2)$$

$$\frac{\text{Maximum speed}}{\text{Average speed}} = \frac{V}{S/T} = r, \quad \text{or} \quad V = r\frac{S}{T};$$

$$\frac{t_r}{t_a} = m, \quad \text{or} \quad t_r = m\, t_a.$$

These values substituted into (2) give—

$$t_a = T\frac{r-1}{r}\ \frac{2}{1+m} \quad \ldots\ldots\ldots \quad (3)$$

and therefore—

$$t_r = T\frac{r-1}{r}\ \frac{2m}{1+m} \quad \ldots\ldots\ldots \quad (4)$$

$$t_c = T\frac{2-r}{r} \quad \ldots\ldots\ldots\ldots \quad (5)$$

$$\text{The acceleration } A_a = \frac{V}{t_a} = \frac{S}{T^2}\ \frac{r^2}{r-1}\ \frac{1+m}{2} \quad \ldots\ldots \quad (6)$$

$$\text{The retardation } A_r = \frac{V}{t_r} = \frac{S}{T^2}\ \frac{r^2}{r-1}\ \frac{1+m}{2m} \quad \ldots\ldots \quad (7)$$

For the power P_a (Fig. 3) we get—

$$P_a = M\,A_a\,V + Q\,V\,;\ P_a = \frac{MS}{T}\ \frac{r^3}{r-1}\ \frac{1+m}{2}\ \frac{S}{T} + \frac{QrS}{T}$$

or—

$$\frac{P_a}{QS/T} = \frac{MS}{QT^2}\ \frac{r^3}{r-1}\ \frac{1+m}{2} + r,$$

and similarly—

$$\frac{P_c}{QS/T} = r\,;$$

$$\frac{P_r}{QS/T} = -\frac{MS}{QT^2}\ \frac{r^3}{r-1}\ \frac{1+m}{2m} + r.$$

Denoting MS/QT^2 by B we get—

$$\frac{P_a}{QS/T} = +B\,\frac{1+m}{2}\ \frac{r^3}{r-1} + r \quad \ldots\ldots \quad (8)$$

$$\frac{P_c}{QS/T} = +r \quad \ldots\ldots\ldots\ldots \quad (9)$$

$$\frac{P_r}{QS/T} = -B\,\frac{1+m}{2m}\ \frac{r^3}{r-1} + r \quad \ldots\ldots \quad (10)$$

Similarly for the torque we get—

$$\frac{T_a}{Q\rho} = +B\,\frac{1+m}{2}\ \frac{r^2}{r-1} + 1 \quad \ldots\ldots \quad (11)$$

$$\frac{T_c}{Q\rho} = +1 \quad \ldots\ldots\ldots\ldots \quad (12)$$

$$\frac{T_r}{Q\rho} = -B\,\frac{1+m}{2m}\ \frac{r^2}{r-1} + 1 \quad \ldots\ldots \quad (13)$$

For $m = 1$, that is, $t_a = t_r$, these equations take the following form:—

$$\frac{P_a}{Q\,S/T} = + B\,\frac{r^3}{r-1} + r \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (14)$$

$$\frac{P_c}{Q\,S/T} = + r \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

$$\frac{P_r}{Q\,S/T} = - B\,\frac{r^3}{r-1} + r \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$$

$$\frac{T_a}{Q\,\rho} = + B\,\frac{r^2}{r-1} + 1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (17)$$

$$\frac{T_c}{Q\,\rho} = + 1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (18)$$

$$\frac{T_r}{Q\,\rho} = - B\,\frac{r^2}{r-1} + 1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

It will be seen that if we give to m the value 1·0 the corresponding factors altogether disappear from these equations, and r is thus the only remaining variable. If we give to r a definite value then $T_a/Q\,\rho$ is a linear function of $M\,S/Q\,T^2$. The same applies to $T_r/Q\,\rho$. These two values can therefore be graphically represented by straight lines.

In Fig. 4 $O\,A = 1 = T_c/Q$. Plotting $M\,S/Q\,T^2$, which value we will denote B on the horizontal, and assuming various values of r we obtain a system of straight lines for $T_a/Q\,\rho$, equation (17), which are plotted in the diagram, for $r = 1·2$, 1·4, 1·5, 1·6, 1·8, and 2·0, all on the assumption that $m = 1$. $T_r/Q\,\rho$ is obtained by giving negative values to B, equation (17), and is therefore represented by the same straight lines prolonged to the left of the vertical axis. From this diagram we can for any given value of B at once obtain the torque diagram. Take, for instance, $B = 0·3$; for $r = 1·5$ we get $T_a/Q\,\rho = 2·35$ and $T_r/Q\,\rho = 0·35$; $T_c/Q\,\rho$ is, of course, always equal to 1. For m equal to 1—

$$t_a = t_r = T\,(r-1)/r, \text{ or for } r = 1·5,\ t_a = t_r = T/3.$$

It will be seen that $M\,S/Q\,T^2$ represents the ratio between two accelerations, *i.e.*, in whatever units we are working this expression will always be a number. The right-hand sides of the equations (8) to (13) are therefore to be looked upon as multipliers, which will give us the torque if applied to $Q\,\rho$, equations (11) to (13), and will give us power if applied to $Q\,S/T$, equations (8) to (10). The results will be expressed the same units as $Q\,\rho$ and $Q\,S/T$.

Similarly the power diagram can be obtained from Fig. 5, where B is plotted on the horizontal and $P_a/(Q\,S/T)$ $P_r/(Q\,S/T)$ on the vertical. These values can also be obtained from Fig. 4, multiplying the values taken from this diagram by r. $P_c/(Q\,S/T)$ is equal to r, which corre-

sponds to the point where the straight lines shown in the diagram intersect the vertical axis.

The diagrams Figs. 4 and 5 show that there are certain values of B where braking occurs. It is generally desirable to, as far as possible, avoid the braking. This can be done for values of B not exceeding 0·25, by selecting a corresponding value of r from the diagram, but it can also be obtained by increasing the time t_r for the deceleration. The time t_a for the acceleration must then be corre-

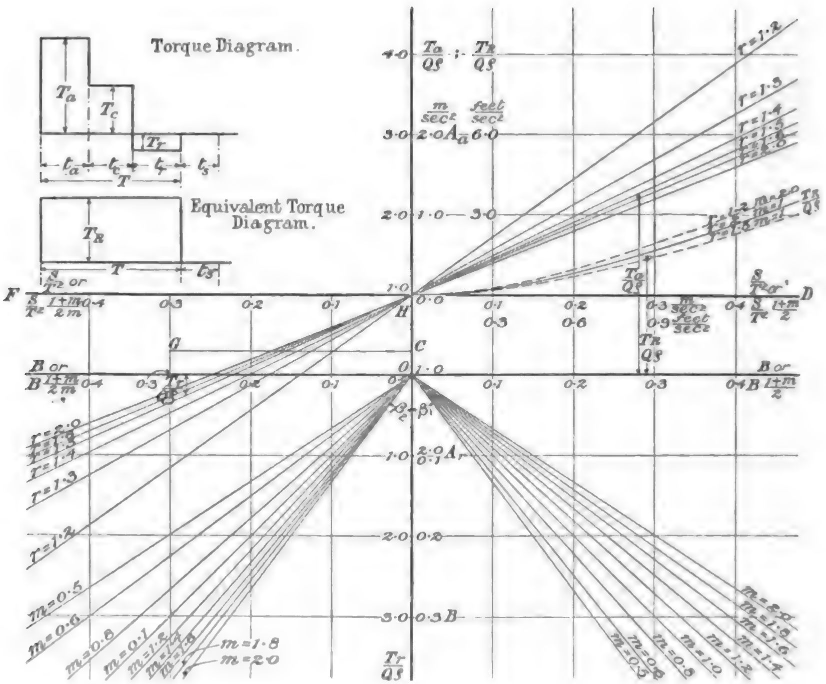


FIG. 4.

spondingly reduced, since with a given value of r the sum $t_a + t_r$ remains constant. This means that m is no longer equal to 1, but has a value larger than 1.

It will be seen from the formula, equations Nos. (14) to (19), that if for B we substitute B $(1 + m)/2$ and B $(1 + m)/2\,m$ these formulæ take exactly the same form as equations (8) to (13). If, therefore, in the diagrams, Figs. 4 and 5, instead of B, B $(1 + m)/2$ is plotted to the right and B $(1 + m)/2\,m$ is plotted to the left, the correct values for torque and power can be taken from this diagram as before. To enable us to see to what extent the value of m influences the torque and

power diagram, lines have been drawn in Figs. 4 and 5 corresponding to the different values of *m* in such a manner that—

$$\tan \beta_1 = (1 + m)/2, \quad \tan \beta_2 = (1 + m)/2\,m.$$

If B is plotted on the vertical from zero downwards and transferred by means of these *m* lines to the horizontal the values B $(1 + m)/2$ and

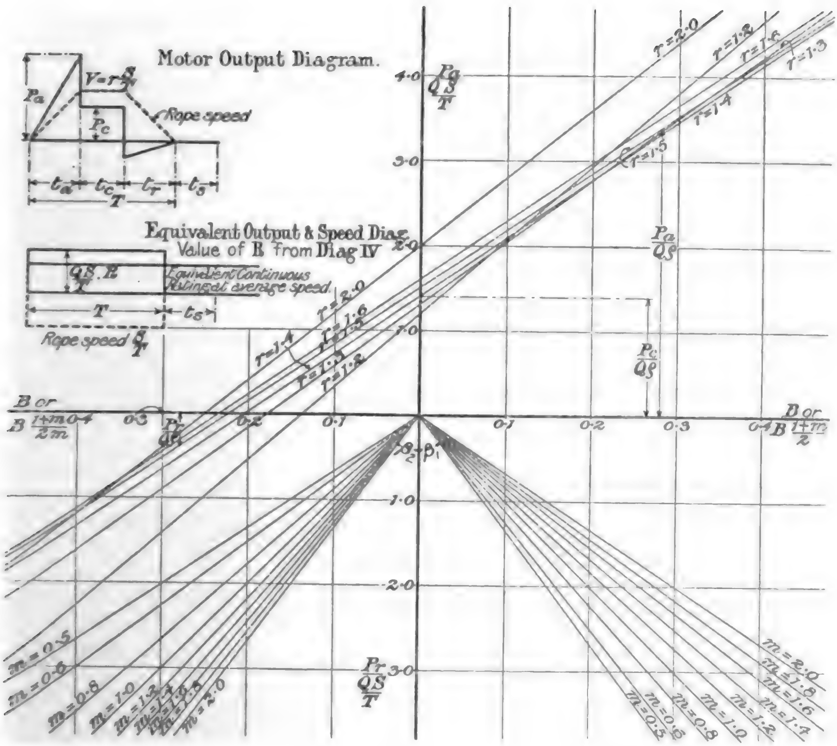


FIG. 5.

B$(1 + m)/2\,m$ are obtained, and the corresponding values for torque and power, corresponding to any given value of *m*, can be read off from the diagrams direct.

In Fig. 5A the values of $(1 + m)/2$, $(1 + m)/2m$, $2/(1 + m$, $2\,m/(1 + m)$, which are the only functions of *m* that enter into the equations, are plotted on the vertical with *m* on the horizontal. From the above it will be seen that if *m* is larger than 1, the acceleration peak of the diagram increases fairly rapidly. The value of *m* smaller than 1 reduces the peak load; but such values can, of course, only come

into question when dealing with low winding speeds, as otherwise T_r/QS will assume too large negative values. From the formula, equations Nos. (6) and (7), it will be seen that the acceleration A_a is equal to $\frac{S}{T^2}\frac{r^2}{r-1}\frac{1+m}{2}$, and that the retardation A_r is equal to $\frac{S}{T^2}\frac{r^2}{r-1}\frac{1+m}{2m}$. If M/Q is made equal to 1—in other words, if in Fig. 4 we plot $\frac{S}{T^2}\frac{1+m}{2}$ on the line A D, the acceleration is obtained as a distance between line A D and the corresponding r line. Similarly the retardation is obtained by plotting $\frac{S}{T^2}\frac{1+m}{2m}$ on the line A F as the distance between this line and the corresponding r line. The accelera-

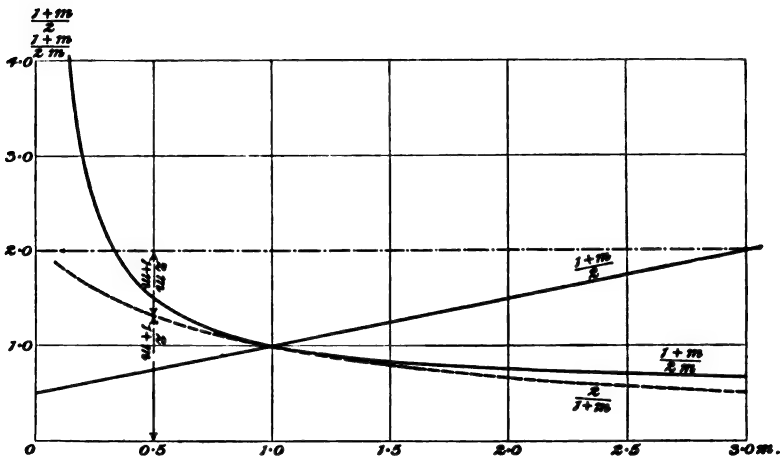


FIG. 5A.

tion and the retardation is then obtained in the same units as S/T^2. As M/Q has a fairly constant value the height of the peaks, that is, the difficulty in designing the winding machinery, depends upon the value S/T^2. The measure of quick winding or slow winding is, therefore, not the average speed S/T, but the value of S/T^2.

If we express the depth of shaft S in metres and the time in seconds the largest value which has hitherto been adopted for any winder is, to the author's knowledge, 0·34, or if expressed in feet and seconds, 1·1. The usual practice for modern fast-winding machines corresponds to a value of 0·2 to 0·25 in the metric system, or 0·65 to 0·82 in the English system.

In starting from rest the acceleration is naturally limited. In practice it is not desirable to exceed an acceleration of 1·3 metres per second per second, or 4·3 ft. per second per second. In the same

manner it is desirable that the braking torque, if at all required, should be kept within limits, not only from the point of view of efficiency, but also to make it easier for the driver to wind to time. Naturally also the danger of an overwind increases with the amount of mechanical or electrical braking required to bring the winder to a standstill in a given time. It may be said generally that the greater the amount of external braking required, that is, the more the actual retardation differs from the natural retardation which the winder would assume if left to itself, the more difficult is it to judge the proper amount of external braking power to apply. It is also to be remembered that, when lowering loads, ever so much greater braking power may be required than when raising loads. It may therefore be said as a general rule that the external braking required for stopping under normal working conditions, if not altogether avoidable, should not exceed one-half to three-quarters of the static torque $Q\rho$.

Electrically driven winders are either controlled by resistance in the ordinary way or else on the Ward-Leonard system. The resistance control involves a considerable amount of losses in the external resistances; but, on the other hand, when the winder is at rest no energy at all is being consumed. The Ward-Leonard system generally necessitates the use of a motor-generator, the motor of which is connected to a constant voltage supply, generally alternating current. The control of the winding motor is then obtained by varying the voltage at the terminals of the motor armature, by means of resistance regulation in the starting dynamo field circuit. The motor field remains all the time at constant excitation. Under such circumstances the torque produced by the winding motor is proportional to the current, the copper losses of the motor armature are proportional to the square of the current, and, therefore, also proportional to the square of the torque. The average value of the (torque)² or of the R.M.S. torque, therefore, determines the copper losses, that is, the size of the motor. Calculated over the running period T of the winder, the R.M.S. torque T_R is as follows (Fig. 2):—

$$T_R = \sqrt{\frac{T_a^2 t_a + T_c^2 t_c + T_r^2 t_r}{T}}.$$

If in this expression all the quantities are expressed in functions of m and r as per equations Nos. (3) to (5) and (11) to (13) we obtain, after some transformation, the following expression:—

$$R = \frac{T_R}{Q\rho} = \sqrt{B^2\left(\frac{1+m}{2}\right)^2 \frac{2}{m}\,\frac{r^3}{r-1} + 1} \quad . \quad . \quad . \quad (20)$$

Examining this expression we find that for given value of B the variation for all values of r and m which come into question is not very considerable. The total amount is at the most $\pm$ 10 B per cent. Considered mathematically the above function has a minimum which is

obtained for $r = 1{\cdot}5$ and $m = 1$. Near this minimum a small variation of r and m has practically no effect at all, so that this minimum value may be considered constant for values of r between $1{\cdot}4$ and $1{\cdot}6$ and values of m between $0{\cdot}8$ and $1{\cdot}2$. It will be seen from equation (20) that for a given B and r there are two values of m which give the same value to R, one of these values being larger than 1, the other smaller than 1; for instance, $m = 2$ and $m = 0{\cdot}5$ will give exactly the same results. In Fig. 4 curves have been drawn showing the value of R or $T_R/Q\rho$. The full line corresponds to the average value, the dotted line below to the minimum value obtained for $r = 1{\cdot}5$ and $m = 1$. The dotted line above corresponds to $r = 1{\cdot}2$ and $m = 0{\cdot}5$ or $2{\cdot}0$, which are the highest values that can come into question. The full line corresponds to $m = 1$, $r = 2$, which gives the formula—

$$\frac{T_R}{Q\rho} = \sqrt{16{\cdot}0\,B^2 + 1}$$

from which the average value of the R.M.S. torque can be calculated.

The iron losses of the winding motor armature are practically proportional to the motor speeds. It follows that for a given motor the iron losses must be the same, whatever the form of the speed diagram. If, therefore, we run the winder during the time T at a speed corresponding to the average speed S/T, developing a torque corresponding to the R.M.S. torque, the losses in the motor will be the same as if the motor was working according to diagram. The losses, therefore, for any given motor will remain practically the same, whichever winding diagram we adopt, if we neglect the variation due to the variation in the R.M.S. value. It further follows that if the efficiency of the motor when running at average speed developing the torque T is η_1, then the efficiency taken over the diagram is—

$$= \frac{1}{1 + R\left(\frac{1}{\eta_1} - 1\right)}$$

For the armature of the starting dynamo we arrive at a similar result. The current in the motor and dynamo circuit is naturally the same. The iron losses, however, do not vary proportionally to the winding motor speed—that is, to the voltage at the starting dynamo terminals. One part of the iron losses are proportional to the square of the voltage, the other and larger part to the $1{\cdot}6$ power. If the iron losses are ascertained at average voltage, and we assume these losses to be proportional to (speed) $1{\cdot}7$, we can calculate the iron loss taken over the diagram, which we obtain as a product of the losses occurring at average voltage and a function of r which has the following form:—

$$\text{Iron loss over diagram} \begin{cases} = \dfrac{3{\cdot}4 - 0{\cdot}7\,r}{2{\cdot}7}\, r^{0{\cdot}7} \times \text{loss at average voltage (motor speed)}, \\ = K_2 \times \text{loss at average motor speed.} \end{cases}$$

It will be seen that for $r=1$, K_2 is equal to 1, and for $r=2$, K_2 is equal to 1·20—in other words, if we assume that the average iron loss calculated over the diagram is equal to the iron loss occurring at the voltage which corresponds to the average motor speed, we introduce an error which in no case exceeds 20 per cent., corresponding to an error of about 10 per cent. of the total loss, or somewhat less than 1 per cent. of the efficiency. It may therefore with sufficient accuracy be said that the losses of the starting dynamo taken over the diagram would be the losses of this dynamo when running at full speed with a current corresponding to the R.M.S. torque of the motor, and with a voltage corresponding to the average speed of the motor. This means that the armature losses which occur when the dynamo runs at full speed, driving the motor at average speed and a load corresponding to the torque T_R, are equal to the average diagram loss both for the motor and the dynamo. If the combined efficiency under these conditions is η_2 the combined diagram efficiency is—

$$= \frac{1}{1 + R\left(\frac{1}{\eta_2} - 1\right)}$$

The efficiency can therefore be fairly accurately tested when running the machines under such conditions. Where required the correction can be applied in accordance with the above formula.

The dimensions of the winding motor not only depend upon the losses in the machine, but also upon the ventilation or the cooling effect, which we will define as the amount of heat dissipated per second for each degree of temperature rise. The influence of a stop naturally depends upon the ratio between the cooling effect at standstill and the cooling effect at full speed. If it is a question of a very badly ventilated motor this ratio is nearly equal to 1, and the stop is of very great influence. If the motor is well ventilated, then the cooling effect at standstill is comparatively small, and the stop, unless it exceeds 15 per cent. of the running time, may be altogether neglected. The cooling effect of a motor at variable speed naturally depends greatly upon the design; but, in any case, one part of the cooling effect may be looked upon as constant at all speeds. This is the cooling effect which occurs at standstill. The cooling effect of certain parts of the motor will increase in direct proportion to the speed, and of other parts of the motor with the square of the speed. The constant part and the part which is proportional to the speed are not influenced by the form of the speed diagram. If we had only these two items to consider, the cooling effect or the ventilation would be equal to that occurring at average speed.

The part of the ventilation which is proportional to the square of the speed will produce an effect proportional to the R.M.S. of the speed diagram. This is easily calculated in the usual manner, and is naturally the smallest for $r=1$, and will reach its maximum for $r=2$. This maximum is 15 per cent. higher. For $r=1·2$ it is 6 per cent.

higher. We find, then, that it is only part of the cooling effect which is influenced by the form of the speed diagram, and that not to a very considerable degree. If we design a winding motor to run at a speed corresponding to $r = 1{\cdot}5$, and afterwards increase the maximum speed of this motor, the cooling effect will slightly increase, but so will also the copper losses, as we have seen when discussing the R.M.S. value of torque. For values of r below $1{\cdot}5$ the ventilation slightly decreases and the copper losses slightly increase, so that when working to such diagrams the temperature of the motor would somewhat increase. From the above it will be seen that the motor losses depend upon the value of B and the average speed S/T. The ventilation also depends upon the value of the average speed S/T, so that the size of the motor can be determined without drawing any speed or power diagrams at all. If the motor is then designed to give the R.M.S. torque at a speed corresponding to S/T, we can, as long as the sparkless running does not stand in the way, use this motor when winding to any speed diagram we like. If the motor is of a badly ventilated type the temperature rise will be the same at all speeds. If it is very well ventilated we may expect a reduction in temperature rise for diagrams corresponding to the higher values of r, but not more than 5 to 10 per cent. for $r = 2$.

Naturally the overload capacity of the winding motor and the starting dynamo have to be considered, but it will be seen from Fig. 4 that for $m = 1$—that is to say, $t_a = t_r$—the maximum torque for such value of r which can come into consideration for any given value of B never exceeds twice the R.M.S. value; in other words, if the designs employed will stand an overload of 100 per cent., special investigations are necessary only when the value of m is larger than 1, or if the stop is of long duration.

The temperature rise of the starting dynamo is also practically independent of the speed diagram, since the total losses, as we have seen, vary only to the extent of a few per cent. The speed of the starting dynamo is practically constant when the Ward-Leonard system is employed, and for the Ilgner system the variation rarely exceeds 15 per cent., in which case the dynamo, so far as temperature rise is concerned, should be calculated for average speed. It is easy to see to what extent the temperature rise of the starting dynamo is influenced by the stop.

In dealing with a winder on the Ward-Leonard system we have to consider separately the constant losses and the variable losses. We have, therefore, in the preceding chapter discussed only the armature losses of the winding motor and starting dynamo, since the motor field losses remain constant, the fields always remaining excited as long as the motor is working. For the field losses of the starting dynamo the average value may be taken, which then is to be considered constant. The windage and bearing friction of the winding motor we have included in the shaft efficiency, so that these losses need not be separately considered. The running of the motor-generator requires

a certain constant amount of energy to overcome the bearing friction and the windage, and to cover the no-load losses in the induction motor. There are, further, the losses occurring in connection with various auxiliary machinery required for the winder, such as air compressor and the no-load energy for the motor-generator for the excitation, if such a machine is provided. All these losses remain constant even when the winder is standing. When the flywheel is coupled to the motor-generator (Ilgner system) these losses become still greater. These losses greatly influence the annual efficiency. If η is the efficiency of a Ward-Leonard or Ilgner winder calculated over a complete winding period, including stop, and f is the load factor—that is, the ratio of hours of full work to the total number of hours, and q the

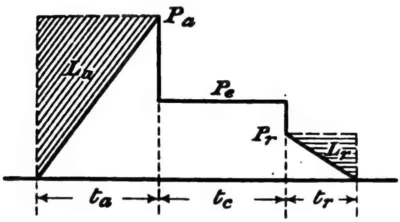


FIG. 6.

constant standby losses expressed in percentage of average input at full work, then the annual efficiency is—

$$\eta_a = \frac{\eta}{1 + \frac{q}{100} \frac{1-f}{f}}.$$

It has already been mentioned that when resistance control is adopted special resistance losses will occur whether the motor is a continuous-current or a 3-phase one. These losses during the starting period must necessarily be equal to the useful work during this period. The conditions during the retardation period may vary; either a certain amount of energy is required during the running-out period or mechanical braking must be applied, or the winder runs out without any application of power in either direction.

As indicated in Fig. 6, if positive power is required the corresponding resistance losses will be equal to the useful work performed, but if braking occurs the losses correspond to the surface indicated in Fig. 7. The work performed by the motor is equal to Q S. The losses during the starting period and retarding period, L_a and L_r, depend upon the shape of the power diagram. With winders of this description we have therefore to consider a diagram efficiency—

$$\eta_d = \frac{Q\,S}{Q\,S + L_a + L_r}.$$

From the diagram Fig. 3, we further get—

$$L_a = P_a t_a/2,\ L_r = P_r t_r/2,\ P_r > 0.$$

Expressing P_a, t_a, P_r, and t_r in terms of r and m, we get—

$$L_a = \frac{QS}{1+m}\left(B\frac{1+m}{2}r^2 + r - 1\right),$$

$$L_r = \frac{QS}{1+\frac{1}{m}}\left(r - 1 - B\frac{1+\frac{1}{m}}{2}r^2\right)$$

and—

$$L = L_a + L_r = QS(r-1),$$

and therefore the diagram efficiency $\eta_d = 1/r$.

If no energy is required during the retardation period, L_r is equal to zero, and we get—

$$L_r = \frac{QS}{1+\frac{1}{m}}\left(r - 1 - B\frac{1+\frac{1}{m}}{2}r^2\right) = 0,$$

$$B\frac{1+m}{2} = m(r-1),$$

and—

$$L = L_a = \frac{QS'}{1+m}[m(r-1) + r - 1] = QS(r-1),$$

and diagram efficiency—

$$\eta_d = \frac{1}{r}$$

We find, then, that if P_r is positive or equal to zero, the diagram

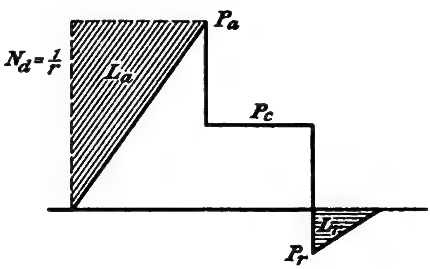


FIG. 7.

efficiency is always equal to $1/r$ whatever the shape of the diagram may be. If P_r is negative, then we get (Fig. 7)—

$$L_a = +\frac{QS}{1+m}\left(B\frac{1+m}{2}r^2 + r - 1\right),$$

$$L_r = -\frac{QS}{1+\frac{1}{m}}\left(r - 1 - B\frac{1+\frac{1}{m}}{2}r^2\right),$$

and—

$$L = L_{e} + L_{a} = QS\left(Br^2 + (r-1)\frac{1-m}{1+m}\right)$$

and diagram efficiency—

$$\eta_d = \frac{1}{Br^2 + (r-1)\dfrac{1-m}{1+m} + 1}.$$

If m is equal to 1, then the diagram efficiency in this case takes the form $\eta_d = 1/(Br^2 + 1)$. If m is larger than 1, the diagram efficiency can either be correctly calculated from the above formula or else be obtained as a very close approximation from the following formula:—

$$\eta_d = \frac{1}{B\dfrac{1+m}{2m}r^2 + 1};$$

this contains the value $B(1+m)/2m$, which is what we require to obtain from Figs. 4 and 5 the torque T_r and power P_r. The diagram efficiency is graphically represented in Fig. 8. Reading—

$$B \text{ or } B(1+m)/2m$$

on the horizontal, we obtain on the vertical the diagram efficiency, in per cent., for various values of r. It will be seen that for any given value of r the diagram efficiency remains constant up to a certain value of B, corresponding to the point where mechanical braking commences to be required (see Figs. 4 and 5). There a certain change occurs in the curve, and for larger values of B the diagram efficiency steadily decreases.

It is easily seen that the armature losses for a continuous-current winding motor may be calculated in exactly the same manner for resistance control as for a Ward-Leonard control. When 3-phase motors are used, the same methods can also be applied in the following manner: The iron losses of the stator core are naturally constant during the whole running period T. The iron losses in the rotor circuit are very nearly proportional to the slip; they are clearly zero for $r=1$, and for any other value of r they are equal to the losses which would occur if the motor was running at average speed. The copper losses may be calculated on the assumption that the magnetising, or the no-load current, remains constant with the energy component, increasing in proportion to the load. The copper losses due to the magnetising current can then be included in the constant losses together with the iron losses in the stator, and the remaining copper losses are then approximately proportional to the torque. The total losses therefore again depend upon the R.M.S. value of the torque, and the total losses in the motor are the losses which would occur if the motor was running during the time T at average speed, that is,

with a slip corresponding to this speed, developing a torque equal to the R.M.S. torque.

The ventilation of a 3-phase motor may be considered on exactly the same lines as in the case of continuous current; that is to say, the cooling effect produced when running according to any speed diagram will be nearly the same as the cooling effect produced when running at average speed. Dealing with the ventilation in this manner, we, as before, somewhat underestimated the cooling effect for the higher values of r, and probably to a somewhat higher degree * than

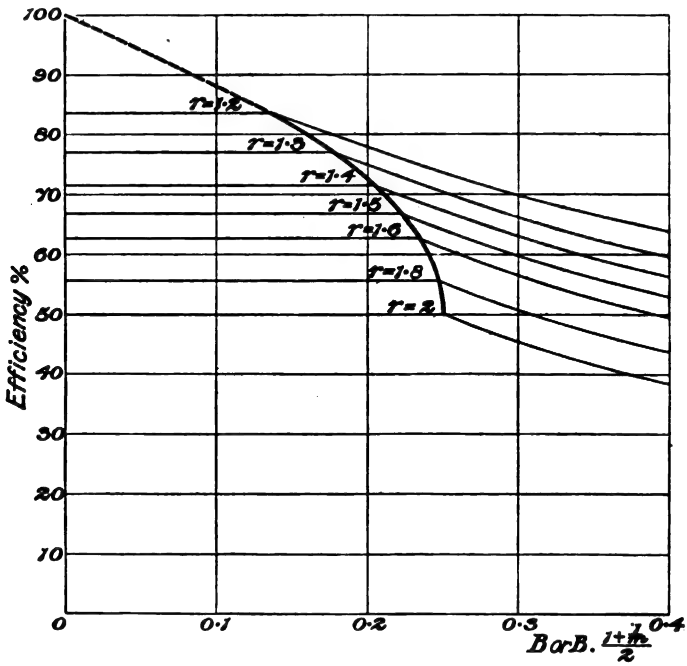


FIG. 8.

in the case of continuous-current open-type motor, since in a 3-phase motor the part of the cooling effect which is proportional to the square of the speed is, as a rule, comparatively large. At any rate, as a first and fairly close approximation, it may be said that the size of a 3-phase motor depends upon the R.M.S. value of the torque and the average speed. In the case of 3-phase motors, we are limited to definite speeds, and therefore for direct coupling only certain definite values of r can come into consideration when the diameter of the drum is fixed. Each of these values of r corresponds to a

* This is, however, compensated by the fact that the copper losses are rather underestimated when dealt with in this manner.

definite synchronous speed, and we can work to other values of r only if we are at liberty to vary the diameter of the drum. If gearing is introduced, then the R.M.S. torque of the motor is reduced in proportion to the ratio of the gearing. If we decide on a certain motor speed, then there is a definite ratio of the gearing $1/a$ which corresponds to the value of $r = 1$. For any other value of r the gearing must be correspondingly reduced to r/a. It follows that the R.M.S. torque for which the motor is to be designed increases in proportion to the value r.

If, therefore, the maximum motor speed has been decided upon, the rated output of the motor will be smaller the lower the value of r. The diagram efficiency is higher the smaller the value of r, and finally it will be seen from Fig. 5 that for any given value of B there is a certain value of r which gives the smallest possible peak load. For values of B larger than 1, this minimum peak load is obtained for $r = 1{\cdot}3$ to $1{\cdot}4$, and even $r = 1{\cdot}5$ gives no great increase of the maximum load. We can further see from Figs. 4 and 5 that with such values of r the braking can be avoided for values of B below 0·22. It will be seen, then, that as long as B does not exceed 0·22 gear-driven winders with resistance control can be very nicely adapted to the work. The only real difficulty to be considered is in connection with the peak load, but as long as the generating station is large enough to deal with the loads occurring, this system is most certainly to be recommended, and the more so the smaller the value of B. For values of B above 0·22 the Ward-Leonard control or the Ilgner system is preferable, and becomes indispensable when B approaches the value 0·3. Above this value the cylindrical drum is less serviceable, and types of drum such as the conical or cylindro-conical types should be considered, which, whilst increasing the braking effect produced by the load during the retardation period, considerably reduce the peak load during the starting period. For $B = 0{\cdot}22$ and $r = 1{\cdot}5$ we obtain from Fig. 8 a diagram efficiency of 0·67. For medium-size winders and moderate speeds an overall efficiency of the motor, taken over the diagram, of 0·88 is easily obtainable, so that with a shaft efficiency of 83 per cent. and 98 per cent. efficiency of the gearing, the overall efficiency of such a winder would be approximately 50 per cent. For smaller values of B, for instance, $B = 0{\cdot}14$, a diagram efficiency of 84 per cent. is obtainable, which under otherwise similar circumstances would give us an overall efficiency of about 62 per cent.

When electric winders were first introduced no gearing had as yet been put on the market which could be considered safe, reliable, and efficient for transmitting large powers. Except for small winders the direct coupling of the motor to the winding drum was the only arrangement considered. During the last few years, however, the leading makers of machine-cut double helical gear have put on the market gears capable of transmitting several thousand horse-power, and are now willing to quote for such gears to transmit any desired power. As long as the ratio of reduction does not exceed 1 : 10, they guarantee

efficiencies of 98 per cent. and absolute silent running of the gear. Gearing of this sort naturally cannot come into question in connection with steam winders. The electric motor with its even torque, capable as it is of starting free from shock and jerks, has here opened new possibilities which are sure to receive considerable attention in the future, particularly in connection with direct 3-phase winders. This particular type of winder is, as is well-known, difficult to arrange for direct coupling. At the usual periodicity (50 periods) it is difficult to build the induction motor for the usual slow-drum speeds in an efficient manner. Its power factor is very bad, and its efficiency comparatively low. Furthermore, we are tied to definite speeds, and such a motor is very expensive. With gearing, however, it is possible to obtain such speeds for the motor that it can be designed for a high efficiency and high power factor, and generally we can obtain so much better conditions, that even if the losses of the gearing amounted to 10 per cent. and more it would pay to introduce it. With 98 per cent. efficiency of the gearing the saving will generally amount to at least 10 per cent. as compared with the direct-coupled winder.

One difficulty with the ordinary type of double helical gearing when employed in connection with reversible machines, such as winders, was that the wear was considerably more when running in one direction than in the other. Lately, however, the so-called "fish-bone" type of gearing has been tried, and has given very satisfactory results. With this type of gearing the wear is the same in both directions of rotation. Although gearing of this sort is fairly expensive, the total cost of motor and reduction gear is considerably less than that of the direct-coupled motor.

From the above we get for the calculation of the winding motor the following formula, where S is in feet, Q in lbs., and T in seconds.

The motor must at average speed—

$$N_a = S/T \times \frac{60}{2\pi\rho} = \frac{9{\cdot}55}{\rho} \times \frac{S}{T} \text{ revs. per minute,}$$

give an output—

$$H_a = Q\,S\,R/550\,T \text{ horse-power (British units),}$$

with specified temperature rise intermittently with a ratio—

$$\frac{\text{Time of work}}{\text{Time of rest}} = \frac{T}{t_s}.$$

The corresponding continuous output H_a' at speed N_a depends upon the design, but if t_s is not more than 20 to 30 per cent. of T, we may put—

$$H_a' = H_a \sqrt{T/(T + t_s)}.$$

With the same torque the output of the motor at full speed, $N = r\,N_a$, would be—

$$H = r\,H_a',$$

but the temperature rise would be less, corresponding to the better ventilation, and for a 3-phase motor also on account of the absence of rotor iron losses.

If the motor is geared in ratio $1 : a$, then the average motor speed is $n_a = a\,N_a$, the full speed is $n = r\,n_a = r\,a\,N_a = a\,N$, and if η_1 is the efficiency of the gear—

$$h_a = \frac{Q\,S\,R}{\eta_1 \times 550\,T} \text{ at speed } n_a \text{, intermittently,}$$

or—

$$h_a' = h_a \sqrt{T/(T + t_s)} \text{ continuously,}$$

at the given temperature rise.

Output at full speed with the same torque—

$$h = h_a' \times r.$$

If the maximum speed n of the motor is given, then—

$$n_a = n/r = a\,N_a, \quad a = n/r\,N_a.$$

For the output in horse-power we get the same formula as before. Since n is given, h increases in proportion to r, that is, although the full speed of the motor is the same, the corresponding output of the motor at full speed varies with r. If, for instance, a 500-H.P. motor at 375 revs. per minute will do the work with $r = 1{\cdot}2$, we have to employ a $(2/1{\cdot}2) \times 500$ or 830-H.P. motor, 375 revs. per minute, if we work to $r = 2{\cdot}0$, and as the average speed would be for the 500-H.P. motor $n_a = \frac{375}{1{\cdot}2} = 310$; for the 830-H.P. motor, $n_a = 187$; the latter motor must, as regards temperature rise, be more amply rated or a still larger type selected. The value of r has, as we have seen, a very considerable influence both on efficiency and size of motor (particularly if gear-drive is employed). If controlled by resistance, r should have the smallest possible value which will enable us to work without braking and without exceeding the largest value allowed for the acceleration (A_m).

Turning the question the other way round, we may say that for each value of r there is a definite largest value of B, which we will call B_m, for which it is possible to draw a speed diagram such that the acceleration does not exceed A_m and no braking occurs; the value of B_m depends, as may easily be seen, upon the product $A_m \times M/Q$.

In Fig. 9 the curves a, b, c, and d give the corresponding values of B_m and r for—

$$A_m \times M/Q = 1{\cdot}0,\ 1{\cdot}2,\ 1{\cdot}4, \text{ and } 1{\cdot}5,$$

corresponding to—

$$A_m = 0{\cdot}91,\ 1{\cdot}09,\ 1{\cdot}27, \text{ and } 1{\cdot}36\ \frac{\text{metres}}{\text{sec.}^2} \text{ for } M/Q = 1{\cdot}1,$$

or to—

$$A_m = 0{\cdot}83,\ 1{\cdot}0,\ 1{\cdot}17, \text{ and } 1{\cdot}25\ \frac{\text{metres}}{\text{sec.}^2} \text{ for } M/Q = 1{\cdot}2,$$

all in metric units. For the corresponding value of the diagram efficiency the curves a', b', c' and d' have been drawn. The maximum torque $\frac{T_a}{Q\rho}$ for such values of B and r is—

$$T_a/Q\rho = 1 + A_m M/Q,$$

or 2·0, 2·2, 2·4, and 2·5 for the curves a, b, c, and d in the order mentioned. To make the diagram complete the value of R is plotted below the horizontal axis. This diagram gives all the information required for the preliminary calculation of a winding motor for resistance control.

If Ward-Leonard control is employed, the smallest motor and best efficiency is obtained for $r = 1·4$ to $1·6$ and $m = 0·8$ to $1·2$. $r = 1·5$ is therefore the correct value as long as A_a does not exceed what we consider the upper limit. For $M/Q = 1·0$ to $1·2$ we get the following table for B, r, and A_m, which is taken from Fig. 4 :—

r.	Am.	B.
1·5	1·0	0·222–0·266
1·6	1·0	0·235–0·282
1·8	1·0	0·247–0·296
2·0	1·0	0·250–0·300
1·5	1·2	0·266–0·320
1·6	1·2	0·266–0·338
1·8	1·2	0·297–0·356
2·0	1·2	0·300–0·360

(See also Fig. 9.)

Cylindrical Drum without Balance Rope.

If we add the torque produced by the unbalanced rope to the torque diagram calculated on the assumption that a balance rope is used, we obtain the torque diagram for unbalanced rope.

If s_a is the travel of the cage during the acceleration, s_r the travel during retardation, l the weight of rope per unit length, and W the weight of rope of length S, then we get—

$$s_a = \frac{V . t_a}{2} = S(r-1)\frac{1}{1+m},$$

$$s_r = \frac{V . t_r}{2} = S(r-1)\frac{m}{1+m},$$

which gives—

$$s_a + s_r = S(r-1).$$

For $m = 1$—

$$s_a = s_r = S\frac{(r-1)}{2}.$$

The rope torque at the beginning of time t_a (Fig. 10) is $W\rho$, at the end of time t_a it is $(W - 2\,l\,s_a)\,\rho$; at the beginning of t_r it is $(W - 2\,l\,s_r)\,\rho$, and at the end of t_r is equal to $-W\rho$. The torque diagram then takes the form of Fig. 10.

We get then—

$$\frac{T_a'}{Q\rho} = \frac{T_a}{Q\rho} + \frac{W}{Q} \quad . \quad . \quad . \quad . \quad (21)$$

$$\frac{T_c'}{Q\rho} = \frac{T_c}{Q\rho} + \frac{W}{Q}\left(1 - (r-1)\frac{2}{1+m}\right) \quad . \quad . \quad . \quad . \quad (22)$$

$$\frac{T_c''}{Q\rho} = \frac{T_c}{Q\rho} - \frac{W}{Q}\left(1 - (r-1)\frac{2\,m}{1+m}\right) \quad . \quad . \quad . \quad . \quad (23)$$

$$\frac{T_r'}{Q\rho} = \frac{T_r}{Q\rho} - \frac{W}{Q} \quad . \quad . \quad . \quad . \quad (24)$$

The values of $T_a/Q\rho$, $T_c/Q\rho$, and $T_r/Q\rho$ are obtained from equations (17), (18), and (19), or Fig. 4.

The R.M.S. torque may be calculated in much the same manner as when balance rope is used, but the general expression is much more complicated. It will be found, however, that m and r in this general expression occur in combinations which give nearly constant values for all values of r and m which can come into question, and that taking into consideration the actual shape of the torque curve (Fig. 10), the R.M.S. torque may be calculated from the following formula :—

$$\frac{T_{R_0}}{Q\rho} = R_0 = \sqrt{R^2 + 0{\cdot}7\,.\,\frac{W^2}{Q^2} + 4\,B\,\frac{W}{Q}\,r\,\frac{3-r}{2}} \quad . \quad . \quad . \quad (25)$$

R is obtained from equation (20), and is the R.M.S. value $T_R/Q\rho$ for a balanced rope. As has been explained before, R is a minimum for $r = 1{\cdot}5$ and $m = 1$; the second term is constant, and the third is a maximum for $r = 1{\cdot}5$. For small values of W/Q, R_0 therefore has a minimum at about $r = 1{\cdot}5$, but for larger values it becomes practically independent of r. $r\,\frac{3-r}{2}$ varies from $1{\cdot}0$ for $r = 1$ and $r = 2$, and is equal to $1{\cdot}12$ for $r = 1{\cdot}5$. If we substitute an average value $r\,\frac{3-2}{2} = 1{\cdot}08$, we get—

$$R_0 = \sqrt{R^2 + 0{\cdot}7\,W^2/Q^2 + 4{\cdot}32\,B\,W/Q} \quad . \quad . \quad . \quad . \quad (26)$$

In Fig. 11 R_0 is plotted as a function of B for $W/Q = 1{\cdot}0$, $0{\cdot}75$, $0{\cdot}50$, and $0{\cdot}25$, and each time for $r = 2$, $1{\cdot}5$, and $1{\cdot}2$. From this diagram the value of R can be obtained when B and W/Q are given.

If in Fig. 4 we draw a line C G parallel with the horizontal axis at a distance $OC = W/Q$ from O, it intersects the r-lines in points corre-

sponding to such values of B for which the winding can be performed without balance rope and without braking. It will be seen at a glance

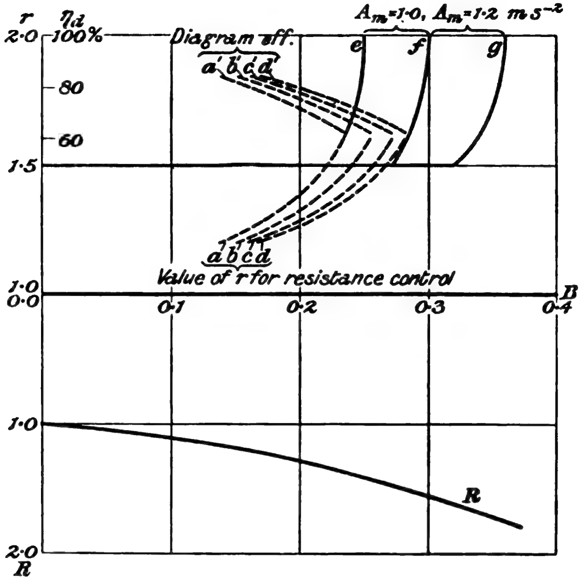


FIG. 9.

that the larger W/Q is the smaller are these values of B. The calculation of the motor otherwise remains the same as before.

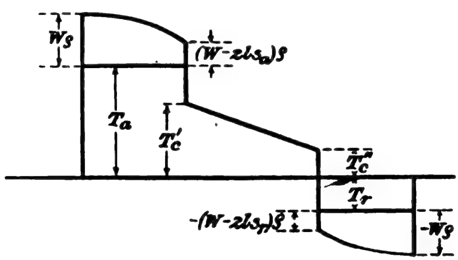


FIG. 10.

Summarising the results of the above investigation they are mainly as follows :—

CYLINDRICAL DRUM WITH BALANCE ROPE.

1. The size of a winding motor for a given arrangement of the mechanical part and a given useful load depends upon the value MS/QT^2 which decides the torque, and the value of S/T which determines the temperature rise.

2. The form of the speed diagram influences the size of the motor when direct-coupled, or for a fixed ratio of gearing, not more than 5 per cent. for values of $M\,S/Q\,T^2$ not exceeding 0·2, and not more than 10 per cent. for values of $M\,S/Q\,T^2$ not exceeding 0·4. With geared motors, if the maximum motor-speed is given, the value of *r* has a very great influence upon the size of the motor, which is then larger the larger the value of *r*.

3. The temperature rise of a winding motor under actual working conditions can be ascertained by running the motor at average speed with a load corresponding to the R.M.S. torque.

4. The electrical efficiency can be ascertained by running the motor at average speed developing a torque equal to the R.M.S. torque.

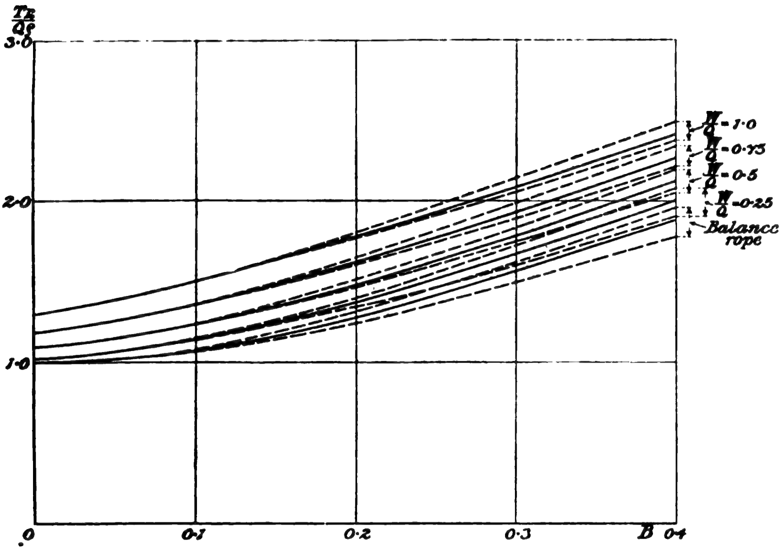


FIG. 11.

5. With resistance control a test as under 4 gives the sum of motor losses and the resistance losses. The motor losses during time T are equal to the motor losses taken over the diagram. The resistance losses stand in the same proportion to the mechanical output as during actual winding if no braking occurs.

6. Resistance control can, with the limitations given in the paper, not be considered for values of B larger than about 0·25. As a rule, in consideration of the peak load the limiting value is smaller still. The most suitable values are B = 0·1 to 0·2.

7. Ward-Leonard control with cylindrical drum can be used for values of B up to about 0·35. With Koepe discs, however, the maximum value of B is about 0·25.

Cylindrical Drum without Balance Rope.

8. The effect of leaving out the balance rope is to increase the R.M.S. value of the torque diagram by about one-half the torque produced by the full length of rope. For values of B smaller than 0·2 the increase is somewhat less, and somewhat more for $B > 0{\cdot}2$.

9. If we desire to work without braking, the value of B for which resistance control is suitable is reduced in proportion to $(1 - W/Q)$, that is, it can only come into question for values of B smaller than about 0·15.

10. Ward-Leonard control can be used within the same limits as before, but the motors are then much larger and the efficiency considerably less.

11. When testing the winding motor as under 5 the diagram efficiency has to be separately dealt with.

12. Different winding systems and best results cannot be correctly compared without taking into consideration the value of $M\,S/Q\,T^2$ and the value of M/Q so far as it is inherent to the system. If no balance rope is used the value R/Q must also be considered.

THE TESTING OF TRANSFORMER IRON.

By LANCELOT W. WILD, Member.

(*Paper received December 22, 1910.*)

When accuracy is the first consideration, transformer iron is doubtless best tested in the form of rings. For routine tests, however, ring specimens are impracticable on account of the cost of winding. For everyday testing transformer iron is generally obtained in strips, which are built up to form some form of magnetic square, the strips being threaded into coils ready wound, and fixed to a base-board.

One form of magnetic square which has been very largely employed is shown in Fig. 1. The strips are built up with butt joints, differently disposed in alternate layers, so that the joint in one layer is covered by continuous iron in the next. This may be called the interleaved butt-joint system with square corners.

The system employed at the National Bureau of Standards, Washington, which may be called the Washington system, is shown in Fig. 2, and has been described by M. G. Lloyd and J. V. S. Fisher.* The strips, which measure 10 × 2 in., are interleaved with strips of paper or other suitable insulating material of the same thickness as the iron. They are then made up into four bundles, which are wound round with tape and inserted into the coils. Corner-pieces are then cut and bent, each to a different length, and these are inserted between the ends of the strips, as shown. A double clamp is finally placed at each corner, and is tightened up so that the strips and corner-pieces are held fast together.

It is customary to allow at the corners an overlap of 2 mm. Assuming that throughout the overlap the flux density is half the normal, the specific loss for the whole specimen should come out too low by a percentage equal to 1·4 times the percentage of overlap. With strips 10 × 2 in. and 2 mm. overlap the overlap works out to 1·4 per cent. of the total length. The correction to be made to the measured specific loss is therefore 1·4 × 1·4, or about 2 per cent. This has to be added to the measured loss, or, as is generally more convenient, subtracted from the total weight. If any other overlap is chosen the correction may be taken as 1 per cent. for each millimetre overlap.

Obviously this correction will vary slightly for different densities, but, as Messrs. Lloyd and Fisher point out, if an ultimate accuracy to

* *Bulletin of the Bureau of Standards*, vol. 5, p. 453, 1909.

1 per cent. is all that is aimed at, it will be quite near enough if we take this correction as constant.

The two chief objections to the interleaved system are, first, that the difference between the longest and shortest path presented to the flux is great; and, secondly, at the corners the cross-sectional area is increased to $\sqrt{2}$ times the normal. At low densities the flux will tend to crowd into the shortest path, and this should increase the specific loss as a whole. At high densities the decreasing permeability will tend to cause the flux to spread out more, and at very high densities, if there is no magnetic leakage, the results obtained will tend to come out correctly.

The objection to the interleaved system can partly be overcome by rounding the corner, as shown in Fig. 3. This renders the cross-section constant at all points of the circuit. One may still, however, expect to get high results at low densities.

The fault that naturally occurs to one with regard to the Washing-

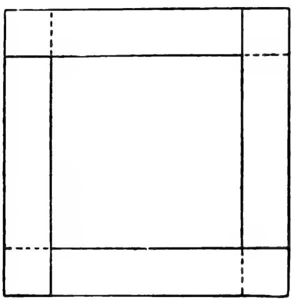


FIG. 1.

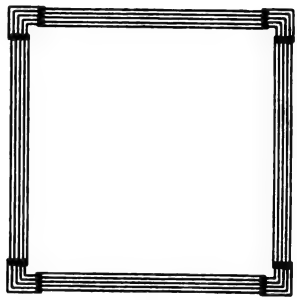


FIG. 2.

ton system is that the cutting and bending of the corner-pieces is likely so to increase hysteresis locally as to vitiate the total measurement. There is also the practical consideration that the operation of making and fitting the corner-pieces takes a considerable amount of time.

In order to arrive at a general idea of the magnitude of the errors involved the author has made comparative tests on four specimens employing all three systems. The strips, which measured 10 × 2 in., were first tested by the interleaved method with square corners. Four strips were then removed, and the remainder made up into bundles for testing by the Washington method. The corner-pieces were cut mostly from the four pieces employed in the interleaved method, but not taken into the bundles. A little additional iron had, however, to be added to make up, as the four strips were only sufficient to make about three-quarters of the corner-pieces.

Tests were made by the Washington method with an overlap of 2 mm., and again with an overlap of 5 mm. The idea was that if the

cutting seriously increases hysteresis locally the effect would be less with the larger overlap, and the difference obtained would give some sort of clue to the amount of the error. In one case a further test was made after imperfectly but certainly partially re-annealing the corner-pieces. A second test by the interleaved method with square corners was then made, in order to show whether the pieces used for the corner-pieces fairly represented the bulk, and finally the ends of the strips were cut, as shown in Fig. 3, and a test was made by the interleaved method with rounded corners. The weight of iron tested was in every case about 4 lbs.

The corner-pieces for the Washington method were cut with ordinary hand shears. As much probably depends upon the sharpness of the shears and the set of the blades, a new pair of shears was obtained for the purpose, and the blades were re-ground before cutting each set of corner-pieces. The corner-pieces were bent up in the vice. Messrs. Lloyd and Fisher suggest that it is advisable to

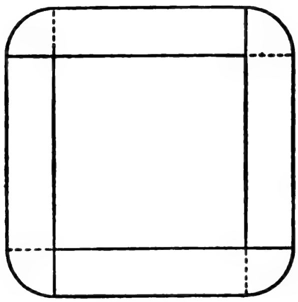


FIG. 3.

obtain a very sharp bend. With lohys the bends were not sharp, but extended throughout about $\frac{1}{16}$ in. of the material. With stalloy, on the other hand, no difficulty was experienced in obtaining sharp bends, the cracking of the scale assisting to cause the bend to take place all along a line.

In adopting dimensions of 10 × 2 in. the author does not suggest that these are the best dimensions for the interleaved method. Possibly 10 × 1 in. would be preferable. It was, however, desirable that as far as possible absolutely the same iron should be tested by both methods.

Magnetising Coils.—For the Washington method four fibre bobbins were constructed, measuring $2\frac{1}{8} \times \frac{7}{16}$ in. inside and $9\frac{1}{4}$ in. long outside cheeks. The magnetising winding consisted of a total of 1,430 turns of No. 14 wound in four layers. Over this was wound half this number of turns of No. 18 for energising the wattmeter shunt. For the interleaved method the bobbins were of the same internal dimensions, but only $7\frac{1}{4}$ in. long. The magnetising winding was 1,440 turns of No. 14, wound in five layers. Half this number of turns of No. 18 furnished the energy for the wattmeter shunt. With practically the same

winding on both sets of coils the voltage, current, and C R drop were practically the same. Instrumental errors were thus neutralised, and form-factor errors were the same for both sets of tests. In the case of the interleaved method the iron was held in place by means of oak wedges driven into the openings of the bobbins. In the case of the Washington tests the iron was held tight by double clamps of brass and oak.

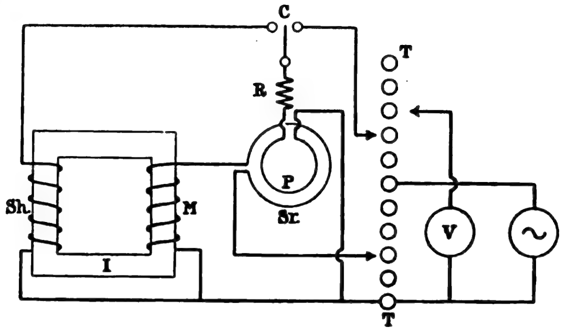


FIG. 4.

Electrical Connections.—The arrangement of the circuits are shown in Fig. 4. The letters refer to the following :—

I Iron under test.
M Magnetising coil.
P Pressure coil of wattmeter.
Sr Series coil of wattmeter.
R Non-inductive resistance, variable to alter range of wattmeter.
T Eleven terminals of an auto-transformer, with ten equal windings.
V Electrostatic voltmeter.
C Two-way switch.
Sh Shunt winding on iron.
∿ Alternator.

The alternator was connected to five sections of the auto-transformer. The electrostatic voltmeter was connected across five sections of the transformer at 50 periods and ten sections at 25 periods. The same reading was thus obtained at both periodicities. The magnetising circuit was connected to one section of the transformer for 2,500 $B_{max.}$, and the lead was moved to include one more section for each additional 2,500 $B_{max.}$ At 12,500 $B_{max.}$ it covered five sections, and then the transformer did not come into the circuit at all. For tests at 2,500, 5,000, and 7,500 $B_{max.}$ the switch was turned to the right. The wattmeter shunt then received its energy from the transformer. This

allowed of the shunt voltage being raised to as much as ten times the magnetising voltage, reducing the minimum range of the wattmeter from 5 watts to 0·5 watt, and thus allowing good readings to be obtained at the lower inductions. With this arrangement the series losses were included in the measurement. It was ascertained by means of an ammeter that up to 7,500 $B_{max.}$ these losses never exceeded 1 per cent. of the iron loss, so as the series losses were almost identically the same for both series of tests they could be neglected. At higher inductions the series losses become serious if included, and at 15,000 $B_{max.}$ and 25 periods the series loss is for thin stalloy of about equal magnitude to the iron loss. For tests at 10,000 to 15,000 $B_{max.}$ the switch was turned to left. The wattmeter shunt then received its energy from the winding on the iron. The amount of this loss could easily be calculated with precision from the voltmeter reading, and was deducted from the total losses.

With stalloy at high densities the form factor of the reactive voltage departed considerably from sine value. At 15,000 $B_{max.}$ and 50 periods it rose no less than 1½ per cent. This was ascertained by connecting a direct-current voltmeter to the shunt winding on the iron through a rectifying commutator. The author has shown that the form factor can be brought back to sine value by adjustment of the wave form of the alternator,* and A. Campbell shows it can be corrected for by testing at two periodicities.†

As, however, the departure of the form factor from sine value was the same for all practical purposes in all series of tests, it was not thought worth while to spend the time necessary for making the correction when so much more work remained to be accomplished.

It may be objected that the voltmeter connected to the transformer did not correctly measure the reactive voltage in the magnetising winding. The series drop rose to a maximum of 4 per cent. of the impressed voltage for stalloy at 15,000 $B_{max.}$ and 25 periods. But then the power factor was so low, only about 0·035, that the difference between the impressed and reactive voltages was only 0·2 per cent. The wattmeter was a reflecting instrument of the dynamometer type with bifilar suspension. It had ranges of 5, 10, 20, and up to 1,000 watts. It was compensated for self-induction by means of condensers shunting the non-inductive resistances. It has been ascertained from tests carried out on a non-ferrous transformer that the phase error on the extremely low power factor of 0·01 does not exceed 1 per cent. at 50 periods.

Comparative Tests: Lohys, 0·0199 *in. thick.*—This specimen which was the first tested was tested at 50 periods only. The results obtained are given in Table A, and the percentage differences found are given in Table B, and also in the form of curves in Fig. 5.

In calculating the percentage differences the interleaved (rounded) method has been taken as the standard, partly because the results

* *Journal of the Institution of Electrical Engineers*, vol. 44, p. 222, 1910.
† *Journal of the Institution of Electrical Engineers*, vol. 43, p. 553, 1909.

Table A.

Lohys, 0·0199 *thick, at* 50 *Periods.*

(Watts per Pound.)

B_{max}.	Washington.		Interleaved.	
	2 mm. Lap.	5 mm. Lap.	Square Corners.	Rounded Corners.
2·5	0·1615	0·159	0·152	0·160
5·0	0·5180	0·512	0·495	0·519
7·5	1·0370	1·030	0·995	1·040
10·0	1·7100	1·700	1·625	1·710
12·5	2·5300	2·520	2·390	2·515
15·0	3·5000	3·490	3·320	3·490

Table B.

Lohys, 0·0199 *thick, at* 50 *Periods.*

(Percentage differences, taking interleaved with rounded corners as standard.)

B_{max}.	Washington.		Interleaved. Square Corners.
	2 mm. Lap.	5 mm. Lap.	
2·5	0·9+	0·6−	5·0−
5·0	0·2−	1·3−	4·6−
7·5	0·3−	1·0−	4·3−
10·0	nil	0·6−	5·0−
12·5	0·6+	0·2+	5·0−
15·0	0·3+	nil	4·9−
Average	0·25+	0·55−	4·8−

obtained by this method come out in an intermediate position, and partly because they appear to be the nearest to the true values.

It will be noticed that the difference between the two interleaved methods averages 4·8 per cent. and is nearly constant throughout, such variations as were found appearing to be accidental. The difference in the two weights is 4·3 per cent. Rounding off the corners increased the watts by 0·5 per cent. only. This suggests that very little flux entered the corners of the square. Increasing the lap from 2 to 5 mm with the Washington method increases the specific loss, after correction has been made for lap, by 0·8 per cent. The difference is greater at low, and smaller at high densities. This difference indicates that the results are on the whole rather high, due to local increase of hysteresis caused by the cutting of the iron. The difference between the Washington and interleaved (rounded) methods is always under 1 per cent. Probably both give rather high results, the Washington due to cutting and bending, the interleaved due to non-uniformity of flux and cutting. There is nothing to indicate that the Washington method leads to superior accuracy.

Lohys, 0·0146 *thick*.—This specimen was tested at 25 and 50 periods. The results are given in Tables C and D and the percentage differences in Tables E and F, and as curves in Figs. 6 and 7.

The iron was tested by the interleaved (square) method twice, both including and excluding the strips from which the corner-pieces for the Washington method were cut. Taking the average of these two sets of tests, it will be seen that the effect of rounding the corners is to raise the specific loss by 4·55 per cent. on the average. The difference is somewhat greater at 50 than at 25 periods and is greater at low than at high densities. It is rather difficult to interpret this variation.

Increasing the Washington lap from 2 to 5 mm. increases the specific loss by 0·3 per cent. on the average. On account of the variations at the various densities one cannot definitely say that cutting has had any appreciable effect on increasing the hysteresis loss.

The Washington (2 mm.) results average 1·35 per cent. higher than the standard. This difference is greater at 25 than 50 periods, and rather indicates that it is due to an increase of hysteresis, probably due to bending. The difference is highest at high densities, and to this extent the results differ from those obtained with the thicker lohys. There is some indication that the interleaved (rounded) method gives high results at low densities due to non-uniformity of flux and the Washington method high results throughout, due not so much to cutting as to the bending of the corner-pieces. As before, there is no indication that the Washington method gives any superior accuracy, but if anything the other way about.

Stalloy, 0·0199 *thick*.—This specimen was tested at 50 periods only. The results obtained are given in Table G, the percentage differences in Table H and graphically in Fig. 8. The effect of rounding off the corners with the interleaved method is to increase the specific loss by 4·8 per cent. on the average, the same amount as for the thicker lohys.

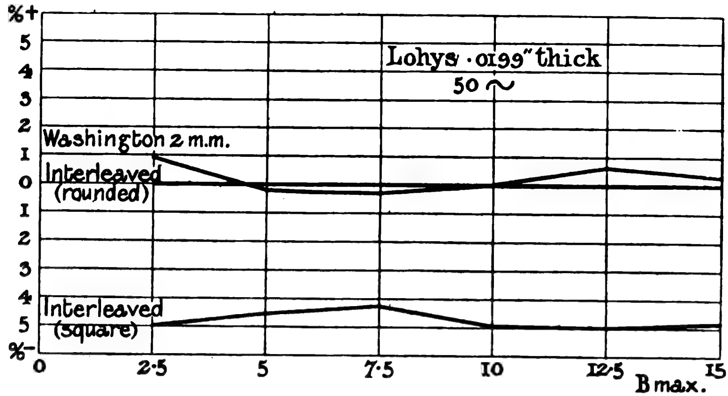


FIG. 5.

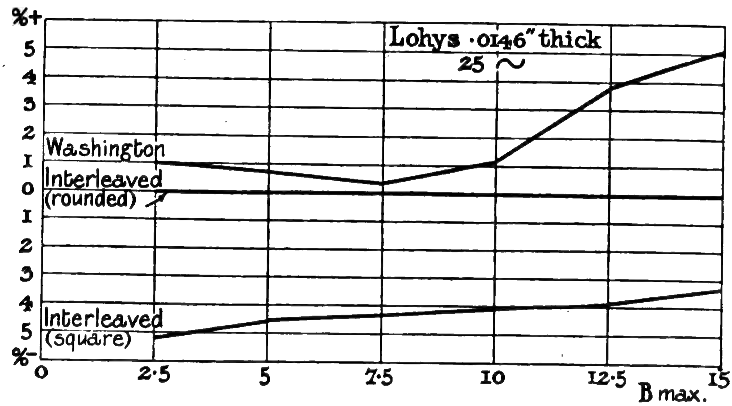


FIG. 6.

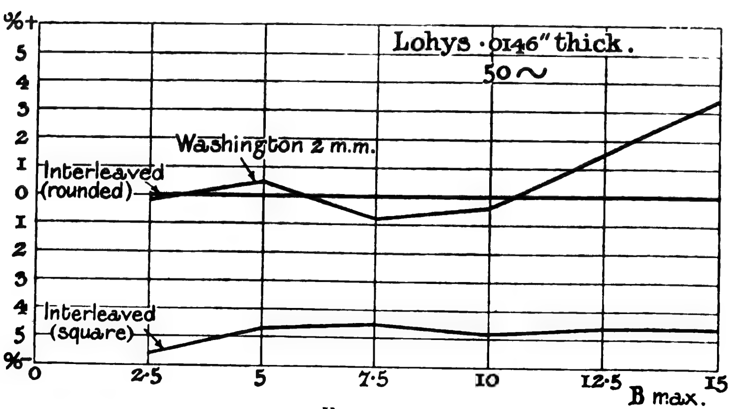


FIG. 7.

TABLE C.

Lohys, 0·0146 thick, at 25 Periods.

(Watts per Pound.)

B_{max}	Interleaved. Square.	Washington.		Interleaved.	
		5 mm. Lap.	2 mm. Lap.	Square.	Rounded.
2·5	0·0554	0·0585	0·0589	0·0553	0·0584
5·0	0·1699	0·1792	0·1797	0·1705	0·1784
7·5	0·3296	0·3440	0·3465	0·3305	0·3455
10·0	0·5380	0·5670	0·5680	0·5400	0·5620
12·5	0·8100	0·8690	0·8740	0·8120	0·8420
15·0	1·1800	1·2760	1·2810	1·1770	1·2190

TABLE D.

Lohys, 0·0146 thick, at 50 Periods.

(Watts per Pound.)

B_{max}.	Interleaved. Square.	Washington.		Interleaved.	
		5 mm. Lap.	2 mm. Lap.	Square.	Rounded.
2·5	0·1246	0·1315	0·1317	0·1246	0·1320
5·0	0·4040	0·4220	0·4260	0·4040	0·4240
7·5	0·7950	0·8260	0·8250	0·7940	0·8320
10·0	1·2930	1·3540	1·3540	1·2950	1·3600
12·5	1·9220	2·0670	2·0550	1·9300	2·0200
15·0	2·7740	3·0150	3·0100	2·7800	2·9100

Table E.

Lohys, 0·146 thick, at 25 Periods.

(Percentage differences, interleaved with rounded corners as standard.)

$B_{max.}$	Interleaved, Square.		Washington.	
	1st Test.	2nd Test.	5 mm. Lap.	2 mm. Lap.
2·5	5·1−	5·3−	0·2+	0·9+
5·0	4·8−	4·4−	0·4+	0·7+
7·5	4·6−	4·3−	0·4−	0·3+
10·0	4·3−	3·9−	0·9+	1·1+
12·5	3·8−	3·6−	3·2+	3·8+
15·0	3·2−	3·4−	4·7+	5·1+
Average	4·3−	4·2−	1·5+	2·0+

Table F.

Lohys, 0·0146 thick, at 50 Periods.

(Percentage differences, interleaved with rounded corners as standard.)

$B_{max.}$	Interleaved, Square.		Washington.	
	1st Test.	2nd Test.	5 mm. Lap.	2 mm. Lap.
2·5	5·6−	5·6−	0·4−	0·2−
5·0	4·7−	4·7−	0·5−	0·5+
7·5	4·5−	4·6−	0·7−	0·8−
10·0	4·9−	4·8−	0·4−	0·4−
12·5	4·8−	4·5−	2·3+	1·7+
15·0	4·7−	4·5−	3·6+	3·4+
Average	4·9−	4·8−	0·6+	0·7+

TABLE G.

Stalloy, 0·0199 thick, at 50 Periods.

(Watts per Pound.)

B_{max}.	Washington.		Interleaved.	
	2 mm. Lap.	5 mm. Lap.	Square.	Rounded.
2·5	0·0845	0·0825	0·075	0·079
5·0	0·2680	0·2620	0·239	0·252
7·5	0·5240	0·5160	0·472	0·493
10·0	0·8540	0·8410	0·767	0·804
12·5	1·2500	1·2320	1·133	1·190
15·0	1·8000	1·7800	1·650	1·730

TABLE H.

Stalloy, 0·0199 thick, at 50 Periods.

(Percentage differences, interleaved with rounded corners as standard.)

B_{max}.	Interleaved. Square.	Washington.	
		5 mm. Lap.	2 mm. Lap.
2·5	5·1−	4·2+	7·0+
5·0	5·2−	4·0+	6·4+
7·5	4·3−	4·7+	6·3+
10·0	4·6−	4·6+	6·2+
12·5	4·8−	3·5+	5·0+
15·0	4·6−	2·9+	4·0+
Average	4·8−	4·0+	5·8+

The variation of this difference at various densities is very small, but shows an inclination to decrease with increase of flux. With the Washington method, increasing the lap from 2 to 5 mm., decreases the average loss by 1·8 per cent. The difference is greatest at low densities. This may be taken as sure proof that the cutting of the corner-pieces has so increased hysteresis locally as to vitiate the results.

The Washington (2 mm.) method gives results on the average 5·8 higher than the interleaved (rounded) method. The difference is highest at low densities. If the cutting of the iron has increased the hysteresis with the Washington method it seems probable that it has also acted in the same way with the interleaved (rounded) method. In this case, however, the length of cut is less and it is probable that at moderate densities the cut portion carries but little flux.

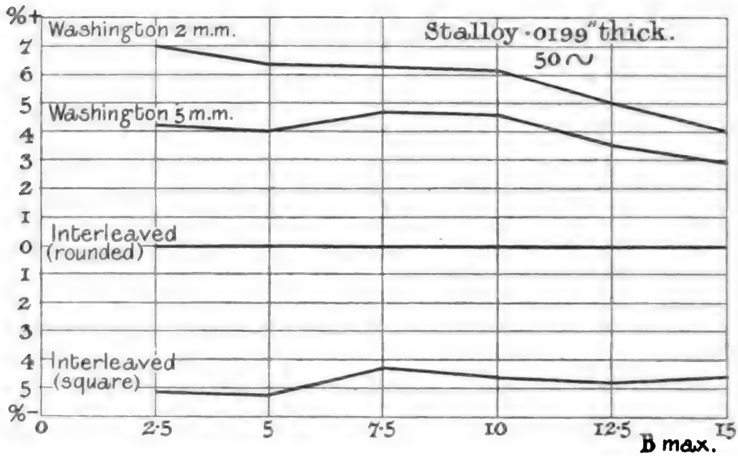


FIG. 8.

It appears quite certain that the interleaved (rounded) method gives high results at all densities. The Washington method which gives still higher results must therefore be considerably more inaccurate.

Stalloy, 0·0139 *thick.*—This sample was tested at 25 and 50 periods. The results are given in Tables I and J, and the percentage differences in Tables K and L, and graphically in Figs. 9 and 10.

Between the first and second interleaved (square) tests there is an average difference of 0·85 per cent. This indicates that the strips used for making the Washington corner-pieces differed considerably from the bulk of the iron initially. This must be borne in mind in making comparisons.

The difference between the second interleaved (square) tests and the interleaved (rounded) tests averages 4·7 per cent., and there is very little variation throughout.

Increasing the lap in the Washington method from 2 to 5 mm.

Table I.

Stalloy, 0·0139 thick, at 25 Periods.

(Watts per Pound.)

B_{max}.	Interleaved. Square.	Washington.			Interleaved.	
		2 mm. Lap.	5 mm. Lap.	2 mm. Lap (Annealed).	Square.	Rounded.
2·5	0·02455	0·0264	0·02595	0·02555	0·0243	0·0255
5·0	0·07850	0·0850	0·08400	0·08280	0·0775	0·0815
7·5	0·15720	0·1703	0·16880	0·16600	0·1550	0·1634
10·0	0·25200	0·2770	0·27550	0·27200	0·2500	0·2620
12·5	0·37500	0·4220	0·41800	0·41200	0·3720	0·3910
15·0	0·52900	0·5990	0·60000	0·59100	0·5250	0·5520

Table J.

Stalloy, 0·0139 thick, at 50 Periods.

(Watts per Pound.)

B_{max}.	Interleaved. Square.	Washington.			Interleaved.	
		2 mm. Lap.	5 mm. Lap.	2 mm. Lap (Annealed).	Square.	Rounded.
2·5	0·0525	0·0516	0·0561	0·0555	0·0522	0·0548
5·0	0·1708	0·1850	0·1830	0·1805	0·1695	0·1783
7·5	0·3430	0·3700	0·3660	0·3620	0·3400	0·3565
10·0	0·5580	0·6060	0·6000	0·5990	0·5540	0·5790
12·5	0·8390	0·9240	0·9200	0·9160	0·8280	0·8660
15·0	1·1750	1·3100	1·3070	1·3010	1·1600	1·2190

Table K.

Stalloy, 0·0136 *thick, at* 25 *Periods.*

(Percentage differences, interleaved, with rounded corners as standard.)

$B_{max.}$	Interleaved, Square.		Washington.		
	1st Test.	2nd Test.	2 mm. Lap.	5 mm. Lap.	2 mm. Lap (Annealed).
2·5	3·7—	4·7—	3·5+	1·6+	0·2+
5·0	3·7—	4·9—	4·3+	3·1+	1·6+
7·5	3·8—	5·1—	4·2+	3·3+	1·6+
10·0	3·8—	4·6—	5·7+	5·2+	3·8+
12·5	4·1—	4·9—	7·4+	6·9+	5·4+
15·0	4·2—	4·9—	8·5+	8·7+	7·1+
Average	3·9—	4·8—	5·6+	4·8+	3·3+

Table L.

Stalloy, 0·0136 *thick, at* 50 *Periods.*

(Percentage differences, interleaved, with rounded corners as standard.)

$B_{max.}$	Interleaved, Square.		Washington.		
	1st Test.	2nd Test.	2 mm. Lap.	5 mm. Lap.	2 mm. Lap (Annealed).
2·5	4·2—	4·7—	3·3+	2·4+	1·3+
5·0	4·2—	4·9—	3·8+	2·6+	1·2+
7·5	3·8—	4·6—	3·8+	2·7+	1·5+
10·0	3·6—	4·3—	4·7+	3·6+	3·5+
12·5	3·1—	4·4—	6·7+	6·2+	5·8+
15·0	3·6—	4·8—	7·5+	7·2+	6·7+
Average	3·8—	4·6—	5·0+	4·1+	3·3+

reduces the average loss by 0·85 per cent., as against 1·8 per cent. for the thicker stalloy. Cutting therefore increases the loss, but not to such an extent as with the thicker material.

After making these two tests by the Washington method the corner-

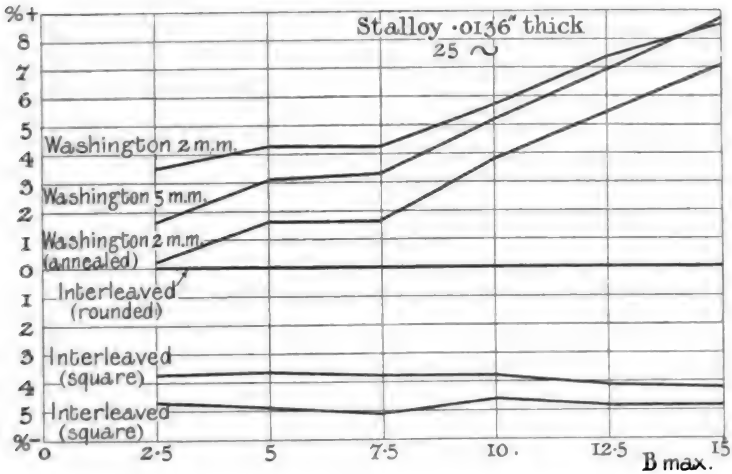


FIG. 9.

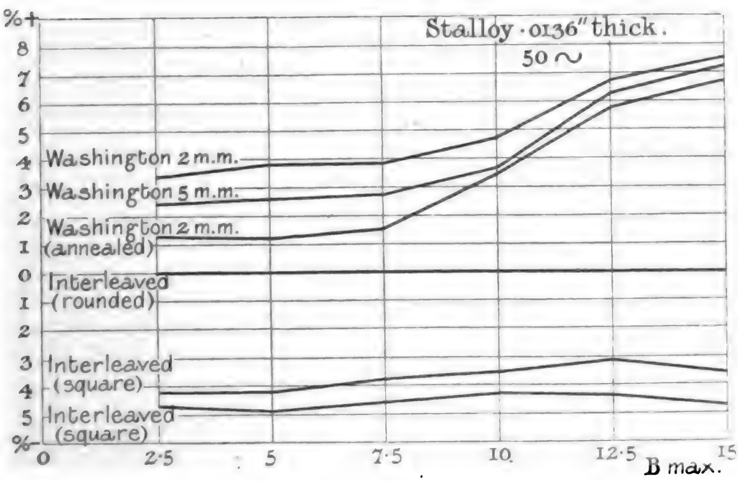


FIG. 10.

pieces were partially annealed. Annealing is a tricky process, and the results obtained depend very much upon the temperature obtained and the rate of cooling. Probably only the makers really know how stalloy should be annealed. It is therefore very likely that the method of

annealing adopted, though reducing the hysteresis loss somewhat, did not bring it nearly down to its original value. Annealing brought down the loss by 2·0 per cent. on the average, the effect being greater at 25 than 50 periods, and greater at low than high densities.

The Washington (2 mm.) method gives results on the average 5·3 per cent. higher than the standard, as against 5·8 per cent. with the thicker material. It would appear that the thinner material is on the whole rather less affected than the thicker by the cutting. It should be noticed, however, that whilst the thicker material shows the greatest difference at low densities, the thinner material comes out highest at high densities.

General Conclusions.—There appear to be two general conclusions that may be arrived at from these tests with a considerable degree of certainty. Firstly, the Washington method is quite unsuitable for stalloy and is of rather doubtful utility for lohys. Secondly, if it should be decided that the interleaved method with rounded corners is the most accurate, it is hardly necessary to trouble about cutting the corners round. If the amount of waste material at the corners is deducted from the gross weight, the results obtained will not differ by more than 1 per cent. from the results that would have been obtained had the corners been rounded.

It appears to the author that the interleaved method is still the best method of testing transformer iron available. It is generally agreed that if accurate results are to be obtained the strips must be annealed after being cut, and this can only properly be done by the manufacturer. There is no special virtue, then, in using wide strips. Strips, say, 10 × 1 would be in many ways preferable to strips 2 in. wide. Corner effects would be reduced by one-half, and, with the same area of iron, the length per turn in the magnetising coil would be reduced, thus reducing the C R drop and improving the form factor.

JOURNAL

OF

The Institution of Electrical Engineers.

Founded 1871. *Incorporated* 1883.

Vol. 46.	1911.	No. 206.

Proceedings of the Five Hundred and Twelfth Ordinary General Meeting of the Institution of Electrical Engineers, held on Thursday, December 8, 1910—Mr. S. Z. de Ferranti, President, in the chair.

The minutes of the Ordinary General Meeting held on November 24, 1910, were taken as read, and confirmed.

The list of candidates for election into the Institution was taken as read, and it was ordered that it should be suspended in the Hall.

The following list of transfers was announced as having been approved by the Council:—

TRANSFERS.

From the class of Associate Members to that of Members—

Samuel Irwin Crookes.
Richard John M. Holmes.
John F. Jones.
Harry Richmond Mott.

From the class of Associates to that of Members—

Joseph Clarke.

From the class of Students to that of Associate Members—

John Edward Catt.
Eustace Jonathan Down.
Walter H. Edridge.
Charles E. Greenslade.
Thomas Saumarez Lacy.
Leonard Solomon.
Kenneth Younghusband.

Donations to the *Library* were announced as having been received since the last meeting from E. W. Cowan, Justus Eck, Messrs. Gauthier-Villars, Lady Kelvin, Sir J. Larmor, The National Electric Light Association, Professor E. Mascart, Messrs. S. Rentell & Co., Ltd.; and to the *Benevolent Fund* from S. E. Britton, to whom the thanks of the meeting were duly accorded.

The following paper, "The Magnetic Properties of Iron and its Alloys in Intense Fields," by Sir Robert A. Hadfield, F.R.S., and Professor B. Hopkinson, F.R.S., Members (page 235), was read and discussed.

THE MAGNETIC PROPERTIES OF IRON AND ITS ALLOYS IN INTENSE FIELDS.

By Sir ROBERT A. HADFIELD, F.R.S., and Professor B. HOPKINSON, F.R.S., Members.

(*Paper first received, August* 17, 1910, *and received in final form, February* 11, 1911. *Read before* THE INSTITUTION *December* 8, 1910.)

The magnetic properties of materials in fields of very high density are of great scientific interest because the relation between B and H which, in the moderate fields employed in practice, or in the ordinary methods of testing, is so complicated and dependent upon so many variables as to defy analysis, then assumes a very simple form. According to the molecular theory of magnetism, as developed by Ewing, the force which opposes the tendency of the magnetic molecules to set themselves in the direction of an externally applied magnetic force is that due to their mutual magnetic actions upon one another. The system of forces caused by these interactions plays a large part in determining the molecular configuration assumed under moderate magnetic forces, and this system is dependent upon the previous history of the material, on stress, temperature, and on other physical conditions. The molecular theory, while it can give a good account of the general behaviour of the material under moderate forces, clearly forbids us to expect that the magnetic properties under such conditions can be quantitatively expressed in simple terms. On the other hand, it predicts equally clearly that if the externally applied force be so great as completely to swamp the effects of the mutual interactions, the magnetic properties will become very simple. Practically the whole of the magnetic molecules then set themselves in the direction of the magnetising force, without regard to their mutual actions. The relation between B and H becomes—

$$B = H + 4\pi I;$$

where I, in the terms of the theory, is the sum of the magnetic moments of the molecular magnets contained in unit of volume.

If it can be assumed that the moment of a molecular magnet is unaffected by the magnetic forces to which it is subjected, the quantity I, in the above equation, is a constant so far as variations of H are concerned, though it might still be affected by temperature and any other physical conditions which can affect the properties

of a separate molecule. The experiments of Ewing and Low * and of Du Bois † show that in iron, nickel and cobalt and some alloys, B does in fact exceed H by a nearly constant amount when H lies between about 2,000 and 25,000 C.G.S. units. These experiments, while they do not negative the possibility of some dependence of the molecular magnetic moment on the external force, give strong grounds for supposing that, at any rate in the materials referred to, the mutual attractions between the molecules are almost completely overpowered by a force of 2,000 C.G.S. units, and that if the force is not more than 25,000 the magnetic moments of the molecules are unaltered by it. The saturation value of 4π I, the constant quantity by which B exceeds H within these limits of the latter quantity is then as definite a physical constant for the material as is the density. Like the density, it may possibly vary with temperature and other physical conditions, but it will probably be unaffected by any change which merely alters the relation of the molecules to one another, and does not alter the internal arrangements of separate molecules. The saturation value of I, expressing as it does the quantity of magnetisable matter in the material, must be regarded as a fundamental magnetisation constant. We propose to call this constant the "magnetism" of the material; or where any confusion can arise with other uses of the word, the "specific magnetism." It appeared that an examination of a series of alloys of iron with carbon and with other metals in fields of very high intensity might lead to results from which some general deductions could be drawn, not only as to magnetic properties, but also as to the constitution of these bodies. The great advantage of the method for this purpose lies in the fact that the saturation value of 4π I in a material consisting of a mixture of substances, is dependent only upon the relative proportions and on the magnetic properties of the several constituents separately, and not on their arrangement in the mass.

Most steels consist of such a mixture of constituents, the arrangement of which is an important factor in the results of magnetic testing of the ordinary kind. The arrangement of the constituents as revealed by the microstructure is dependent upon a great variety of circumstances, and this makes it hopeless to look for any simple quantitative relation between the magnetic properties of an alloy as ordinarily tested and its composition. When the alloy is saturated, however, this complication disappears. Let it be supposed that the magnetic moments of the molecules of the several constituents present are respectively μ_1, μ_2, μ_3, and that the numbers of these molecules per unit volume of the material are respectively n_1, n_2, n_3, ... Then, if H be above the saturation value, but not so large as to affect μ_1, μ_2, we have—

$$I = n_1, \mu_1 + n_2, \mu_2 + .$$

The same result may be expressed without using the language of

* *Philosophical Transactions*, A, vol. 180, p. 221, 1889.
† *Philosophical Magazine*, vol. 29. p. 293, 1890.

the molecular theory if it be supposed that the magnetisms of the several constituents are I_1 I_2 ... per unit of mass, and that m_1 m_2 ... are the masses of the several constituents present per unit mass of the mixture. In that case—

$$I = m_1 I_1 + m_2 I_2 + \ldots \ldots \quad (1)$$

This relation is not dependent upon any molecular theory of magnetisation, but only on the assumptions that there are definite constituents which are mechanically mixed, and that for each there is a definite saturation value of I.

The material for the research was at hand in the form of a series of alloys prepared at the Hecla works. The alloys have already been the subject of extensive investigation, and many of their physical properties are known. In particular, magnetic tests by the magnetometer method have been carried out on many of them, the force used ranging up to 40 C.G.S.* In composition the alloys cover a wide range, including iron-carbon steels, nickel steels, and manganese steels, with varying proportions of the added elements.

Summary of Results.

The following are the most important results obtained from the work so far as it has progressed at present:—

1. Every alloy examined, without exception, has a definite saturation intensity of magnetisation. In most cases this is reached in a field of 5,000 units, but in a few there is a small increase, as between 5,000 and 25,000. The forms of the curves of magnetisation connecting I and H in these exceptional materials, however, leave no doubt of the existence in them also of a saturation value of I. Every one of the materials tested, without exception, behaves as though it consisted of a mixture of magnetic substances with non-magnetic substances having a permeability not differing materially from unity. This holds good also for the non-magnetic or nearly non-magnetic nickel or manganese alloys, and, in this respect, our results differ from those obtained by Ewing and Low—according to whose experiments a nearly non-magnetic manganese steel had a constant permeability of about 1·4. Among all the alloys which we have tested there is none having a constant permeability differing from unity by more than 2 per cent.

2. There is in the series no alloy having a higher specific magnetism than pure iron.

3. The saturation value of I in absolute units for pure iron of density 7·80 is 1,680 within 1 per cent. This is slightly lower than the values obtained by Ewing and Low and other experimenters.

4. In an annealed iron carbon steel in which other elements are present in small proportions the specific magnetism is less than that of pure iron by a percentage equal to six times the percentage of carbon.

* Barrett, Brown, and Hadfield. *Proceedings of the Institution of Electrical Engineers*, vol. 31, p. 674, 1902.

This result constitutes a verification, in the case of annealed iron-carbon alloys of the linear relation (1) above connecting the magnetism of a mixture with the magnetisms of its constituents. In this case there are two constituents, mechanically mixed, viz., pure iron and iron-carbide, the percentage of iron-carbide being 15·5 times that of the carbon in the steel. It is readily deduced from equation (1) that the magnetism of carbide of iron is about two-thirds of that of pure iron.

5. Quenching an iron-carbon alloy from a high temperature reduces the specific magnetism by a large but somewhat uncertain amount.

6. The addition of silicon or aluminium to iron results in a reduction in specific magnetism which is roughly in proportion to the amount added as though the addition behaved as an inert diluent. If carbon be present, however, silicon seems to neutralise its action to some extent. For instance, an alloy containing 2·28 Si and 0·67 C is 3·6 per cent. less magnetic than pure iron, whereas if the carbon had its full effect as in iron-carbon alloys, and the silicon were simply an inert diluent the reduction would be 6·3 per cent.

7. The observations on the alloys of iron with nickel and with manganese, or with both these elements, have failed to reveal any simple relation between their magnetism and their composition. It is probable that this is due to the peculiar effects of heat treatment on these substances. When these effects are sufficiently known it may be possible to apply to the manganese and nickel alloys the same kind of magnetic analysis as we have applied to the carbon steels.

THE ELECTROMAGNETS.

The general dimensions of the magnet on which most of the tests were made are shown in Fig. 1. The vertical limbs are of rectangular section, 10 cm. by 20 cm. The pole-pieces are cylindrical and are made a good fit in holes at the top of the vertical limbs, so that they can slide axially, and be clamped in any position by means of set-screws. The yoke is wound with about 1,600 turns and each pole-piece with about 400 turns of No. 14 S.W.G. wire.

For producing the highest fields the magnet was fitted with the pair of pole-pieces shown in place in Fig. 1. With the tips of these ¼ in. apart, and with a current of 30 amperes passing in the coils of the magnet, the two parts of which were placed in parallel, a field of about 22,000 C.G.S. could be obtained in the space between the flat ends of the pole-pieces. The distribution of the field was determined by means of concentric annular test coils and was found to be constant within 1 per cent. over a circle of 2·5 mm. radius. By increasing the current to 60 amperes, which, however, could only be kept on for a short time, the intensity of the field could be increased to 25,000 C.G.S.

Lower fields ranging up to 10,000 C.G.S. were obtained by replacing the conical pole-pieces, shown in Fig. 1, by a pair of flat pole-pieces having flat faces 1 in. square. With these placed ¼ in. apart with their faces parallel a uniform field of about 7,000 C.G.S. was produced

over an area 20 mm. square with a current of 5 amperes in the magnet coils.

The material was for the most part in the form of rods about 5 mm. diameter. In most cases it was rolled into this form, but a few pieces were forged or cast. The magnetic test-pieces were turned down from these rods into little cylinders $\frac{1}{8}$ in. diameter. They were, in most cases, $\frac{1}{4}$ in. long. The same testing coil was used for all the pieces. It consisted of sixteen turns of No. 38 wire (diameter over insulation 0·057 mm.) wound on a brass bobbin which just fitted over the test-piece. A second coil also of sixteen turns was wound outside the first with a layer of paper between the surfaces, to measure the magnetising force in the neighbourhood of the specimen. As it was not possible to make sufficiently accurate measurements of the dimensions of such

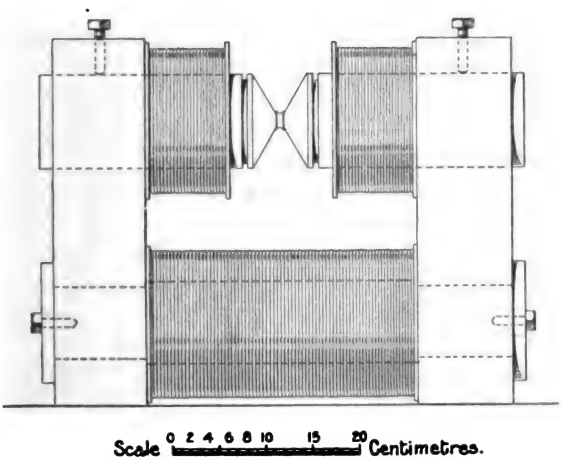


FIG. 1.

small coils, the effective areas were determined by magnetic measurements. The flat pole-pieces were fixed in position about $\frac{1}{4}$ in. apart, and a coil of twelve turns wound on a brass former about 15 mm. diameter was inserted between them. The fling obtained when this coil connected to the ballistic galvanometer and a current of about 5 amperes reversed in the magnet coils, was observed. The test coil was then inserted and connected to the galvanometer and the fling again taken with exactly the same exciting current. The area of the larger coil could be accurately calculated from its dimensions, and that of the smaller deduced from the ratio of the flings after reducing them to the same resistance in the galvanometer circuit. An enlarged section of the specimen, bobbin, and coils when in place is shown in Fig. 2.

The galvanometer used in most of the tests was of the moving coil

type made by Nalder Bros., and had a period of about 16 seconds. A full account of its calibration is given in Appendix I.

In order that the ballistic galvanometer may correctly record the flux change in a coil connected to it, it is necessary that that change should be substantially complete within a period which is small compared with the natural period of oscillation of the galvanometer. In our experiments the flux change was caused by the reversal of the current in the coils of the magnet, and was considerably retarded by the effects of eddy currents and of self-induction. With the flat pole-pieces

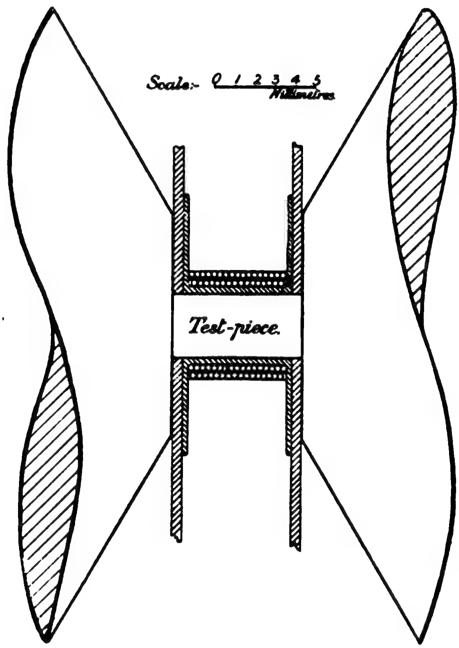


FIG. 2.

and a current of 5 amperes, 5 per cent. of the flux change had still to be completed at the end of 2 seconds. The effect of this was fully investigated, and it was found that while measurements of the absolute value of the flux density based on the moving-coil galvanometer might be subject to an error of several per cent., this error did not materially affect the determination of I. This matter is discussed in detail in Appendix II.; it will suffice to say here that the results obtained with the moving-coil galvanometer were checked by comparison with similar measurements on a suspended magnet instrument (Broca type, made by Cambridge Scientific Instrument Company) of much longer period (about 30 seconds.) Measurements of I for the same piece of

iron obtained with this galvanometer agreed within $\frac{1}{4}$ per cent. with those given by the shorter period instrument.*

In making a test the pole-pieces were gently butted up to the ends of the test-piece and fixed in position. The testing coil was first inserted with a brass dummy in place of the test-piece, the current in the magnet coils was reversed, and the fling observed on the ballistic galvanometer which was connected to the inner coil. The brass piece was then replaced by the iron test-piece, the current again reversed—care being taken that it should have exactly the same strength as before—and the fling again observed.

Let—

- S' be the area of the testing coil.
- S the area of the test-piece, multiplied by the number of turns in the coil—in this case 16.
- I the intensity of magnetisation in the test-piece.
- H the value of the magnetising force before the test-piece is inserted.
- H' the value of the magnetising force after the test-piece is inserted.

Then the flux-change corresponding to the fling obtained with the brass dummy is $H\ S'$, and that corresponding to the fling obtained with the test-piece is $H'\ S' + 4\ \pi\ I\ S$. The difference D of the two flings will therefore, on the same scale, represent—

$$4 \pi I S - (H - H') S'.$$

Since the current and the distance between the pole-pieces is exactly the same whether the dummy or the test-piece be in position, the magnetising force will be the same except in so far as it is disturbed by the introduction of the test-piece. The disturbance so produced is nearly proportional to $4 \pi I S$. Ultimately, therefore, the difference of the two flings is proportional to $4 \pi I S$ and the values of I for two different specimens are in proportion to these differences. This comparison is, to a high degree of accuracy, independent of any knowledge of the correction $H - H'$, and the comparison of I for two specimens based upon it does not involve any accurate knowledge of the area S' of the testing coil, but only a knowledge of the area of the test-piece. The latter can be accurately measured, and it is probable that the ratio of the magnetisms of two steels can be measured by this method with an accuracy of one part in two hundred.

For determining the absolute value of I, however, it is necessary to obtain the absolute value of $H - H'$, the reduction of the magnetising force caused by the introduction of the piece. This was found to be comparatively small in the low fields obtained with flat pole-

* Added February 10, 1911. Since writing the paper this has been further confirmed by comparison of the effect of reversal with that of withdrawing the piece from the field. The two methods agree within $\frac{1}{2}$ per cent.

pieces, but is of serious amount when the conical pole-pieces are used, and a good deal of time was devoted to its determination. The effect of the introduction of the test-piece upon the distribution of magnetic matter which determines the magnetising force is confined to the immediate neighbourhood of the ends of the test-piece, and consists in the addition of a volume and surface distribution of magnetisation in that neighbourhood. This additional distribution consists of three parts, that is :—

1. Over the circular patch covered by the end of the test-piece the surface magnetisation disappears; which may be represented by supposing that there is an additional distribution of density $\pm$ I over this patch which annuls the density $\mp$ I present before the test-piece was inserted.

2. There will be a volume density of magnetisation just under each end of the test-piece, and within the conical pole-pieces due to the spreading of the lines of induction in the latter after they emerge from the test-piece. The general effect of this will be opposite to that of No. 1, and is probably nearly equivalent to that of a surface distribution of magnetism of uniform density over the circular patch.

3. The fringing of the lines of induction at the end of the test-piece gives rise to a surface distribution on the cylindrical surface of the latter near to the end, and associated with this there is a diminution in the surface density in an annulus on the flat face of the pole-piece near to the specimen, where the fringing lines re-enter the iron.

Of these three additions, Nos. 1 and 2 are probably the most important, and the general effect of all may be represented with a considerable degree of accuracy as being the same as that of two circular patches of magnetism of uniform density on the parts of the pole-faces covered by the test-piece. It is easy to calculate the magnetic effect of two such patches in any coil of given dimensions,* and by measuring the absolute amount of the diminution of flux in the annular space between two coils surrounding the iron specimen produced by the introduction of the specimen, the appropriate density of magnetisation can be determined. For this purpose two testing coils were used; one (A) has already been described and is figured in Fig. 2. In the other coil (B) as in coil A there were 16 turns on the inner winding and 16 turns on the other, so that by placing these windings in opposition the flux in the annular space between them could be determined. The inner winding B was wound on a former of the same size as the specimen, and the outer on an ebonite bobbin which was just large enough to be slipped over the inner coil on its former. The former was then withdrawn so that the iron test-piece could be inserted. It will be seen that in coil B the inner winding is very much closer to the specimen, and that a larger average effect will be produced in the annulus than in the case of coil A. It was found that the reduction in magnetising force in the annulus of either coil was very closely the same as that which would be caused by a patch of mag-

* See Appendix III.

netism of density $\pm 0{\cdot}8$ I on each end of the test-piece. The experiment consisted simply in keeping the position of the magnet-poles fixed, exciting the coils with a current of about 30 amperes, and observing the fling produced by reversal first with a brass dummy, and secondly with a piece of Low Moor iron in position. The experiment was repeated a great number of times, brass and iron being inserted alternately in order to eliminate accidental differences between the conditions with and without the iron test-piece. The following table shows the average results which are certainly correct within half a division, together with the differences calculated on the above supposition that they are due to two patches of magnetism of density $\pm 0{\cdot}8$ I.

	Reduction of Fling in Annulus Coil. A	B	Correction on D. A	B
Observed	$9\frac{1}{4}$	$15\frac{1}{2}$	—	—
Calculated	$9\frac{1}{2}$	$14\frac{1}{2}$	$20\frac{1}{2}$	$15\frac{1}{2}$

In the same table are shown the corrections which must be applied in the case of each coil to D which is the increase in the fling due to the inner coil when iron is introduced in place of the dummy. These corrections are equivalent to the quantity $(H - H')_1 S'$, and when added to the observed value of D give the fling corresponding to 4π I S for the specimen. In the case of the piece used in this experiment, the value of D with coil A was 121 divisions, and with coil B 124 divisions, so that the corrected values of the fling would be $141\frac{1}{2}$ and $139\frac{1}{2}$ respectively. These, of course, ought to be the same, and for finally calculating the correction it has been assumed that the true value of 4π I S is $140\frac{1}{2}$ for this piece. The correction to be applied with coil A is then $19\frac{1}{2}$ divisions or $13{\cdot}9$ per cent. of 4π I S. In other words, the observed fling must be multiplied by $1{\cdot}16$ in order to arrive at the fling corrected for end effect.

The above calculation of the correction for end effect is based on the assumption that it may be regarded as due to a uniform distribution over the two circular ends of the specimen. This, of course, is not quite accurate, but that it is not far from the truth is shown by the fact that the surface density which must be assumed in order to account for the observed changes in H is four-fifths of I, from which it appears that the most important term in the added distribution is that due to the blotting out of the magnetism on the parts of the surface covered by the test-piece, and for this part, of course, the assumption of uniform distribution is very close. That the manner of distribution of the magnetism does not make a great difference in the result, however, can be shown by taking an alternative, but probably much less accurate, assumption, namely, that the whole of the added magnetism may be supposed to be concentrated at the centre of the circular patch. In that case the differences to be expected in the annulus coils A and B and the corresponding corrections to be added to D as determined from these coils are as follows :—

	Reduction of Fling in Annulus Coil. A	B	Correction on D. A	B
Calculated	9¼	13½	23¾	18½
Observed	9¼	15½	—	—

The values of 4π I S obtained by applying this correction would be 144¾ and 142½ respectively, the mean being 143¼ as against 140½ when the correction is calculated on the assumption of uniform distribution. It seems probable that the latter assumption leads to a value of 4π I S, which is within 1 per cent. of the truth. The fact that the correction is four-fifths of that produced by the patches of magnetism on the ends of the test-pieces, shows that it must be closely proportional to the values of 4π I S, and a correcting factor 1·16 has been applied for all the specimens.

In the case of the lower fields obtained with the flat pole-pieces the correction for the ends can be determined by direct experiment. In this case it may be regarded as equivalent to an addition to the length of the test-piece due to the fact that the pole-pieces, which before the introduction of the test-piece are but slightly magnetised (the maximum flux density under these conditions is 10,000 C.G.S.) become fully saturated over a short distance within the metal just under the parts covered by the ends of the test-piece. The joints between the test-piece and the pole-pieces slightly increase this effect. In order to determine the amount of the correction in this case the following experiment was made. Two pieces of Low Moor iron were turned up, each 1½ in. long and ⅜ in. in diameter. The value of D was determined for each of these pieces, the pole-pieces being separated by a distance of 1½ in. to admit it and the current in the magnet coils being increased to about 30 amperes, which gave a field of about 5,000 C.G.S. when the piece was not there. The middle, ⅝ in. of the piece, was then cut out and the value of D again determined for the shortened piece. Finally the length of this piece was reduced to ¼ in., being the central quarter of the original 1½ in., and the value of D determined for this short length. The magnet current was adjusted in each case to give H about 5,000 C.G.S. The results are shown in the following table:—

Length of Piece:—		1½ in.	⅝ in.	¼ in.
Fling D	1st piece ...	230¾	229	227
	2nd piece ...	232	231¼	229½

from which it appears that the value of D for a piece 1½ in. long is about 1½ per cent. greater than for a piece ¼ in. long. For an infinitely long piece, in which the end effects would be absent, the difference would be rather under 2 per cent. This is the correction which has been applied in all cases to tests in the low fields.

In the first series of systematic tests of the alloys the value of H′, the magnetising force within the piece, was determined by measuring the flux density in the annular space between the two layers of the coil. This was the method adopted by Ewing and Low, who measured the

flux density in an annular space surrounding the neck of the piece and assumed that it was the same as that in the piece. In their case, at any rate when using highly magnetic materials, the assumption was probably nearly correct, for the pole-pieces were so shaped as to give a very uniform field with the iron specimen in place. We, at first, made a similar assumption, but the investigation which is outlined above shows that it is not in accord with the facts when applied to the intense fields produced by our conical pole-pieces. The field in the annulus is diminished by the insertion of the test-piece owing to the influence of the circular patches of magnetism, but it is not diminished so much as is the magnetising force in the centre of the iron. Calculated on the above assumption that the end effect may be represented as due to two circular patches of magnetisation on the ends of the piece of density $\pm 0{\cdot}8$ I, the diminution in the average magnetising force in the annulus amounts to $0{\cdot}047 \times 4\pi I$. If, therefore, H′ (the average value of the axial component of magnetising force over the area of the inner coil) be assumed to be reduced in the same proportion as the magnetic force in the annulus, the correction $(H - H')\,S'$ will amount to—

$$0{\cdot}047 \times 4\pi I S \times \frac{S'}{S} = 0{\cdot}079 \times 4\pi I S,$$

whereas it should be $0{\cdot}139 \times 4\pi I S$. Thus the value of $4\pi I S$ will be underestimated by 6 per cent. if H′ be taken as given by the field in the annulus.

When the flat pole-pieces and more moderate fields are used, there is also a slight reduction in the annulus field when the piece is inserted. This was found by experiment to amount to about $\frac{1}{100}$ of $4\pi I S$ with a piece $\frac{1}{4}$ in. long and a field of about 7,000 C.G.S. Here again the value of H′ is rather less in the iron than in the annulus; a correction of $1\frac{1}{4}$ per cent. has still to be added to the estimate of $4\pi I S$ based on the assumption that the magnetising force is the same in the annulus as in the test-piece.

At a later stage in the research another magnet was brought into use. The limbs and yoke of this instrument were formed of transformer plates, insulated by sheets of paper, the section of the iron being 32 sq. cm. They were wound with two coils of 2,200 turns each No. 18 S.W.G. copper wire. The pole-pieces were solid and of Low Moor iron, and had flat opposed faces 3·8 cm. in diameter. Two testing coils were used, each consisting of 16 turns of No. 30 S.W.G. copper wire wound on a thin brass tube. The two coils were connected together with their axes parallel. The areas of these coils were adjusted to exact equality, which could be tested by connecting them in series and in opposition between the parallel faces of the magnet poles and reversing the current. They were used differentially, the piece to be tested being inserted in one of the coils. The fling in the galvanometer is then proportional to $4\pi I S$ for the piece, subject, however, to the end correction. The special advantage of this method is that the magnetising force H is automatically deducted from the

observed B at the moment of measurement, instead of being determined in a separate experiment. This is of especial importance where it is desired to test an alloy which is nearly non-magnetic. It was easy in this way to detect magnetism amounting to less than $\frac{1}{100}$ part of that of pure iron and to measure the magnetism of a nearly non-magnetic alloy to within that amount. In some cases where it is desired to test an alloy which is highly magnetic, a standard piece of pure iron can be put in the other coil; the difference between the magnetism of the alloy and that of pure iron is then measured directly by the galvanometer fling. The galvanometer can be calibrated at

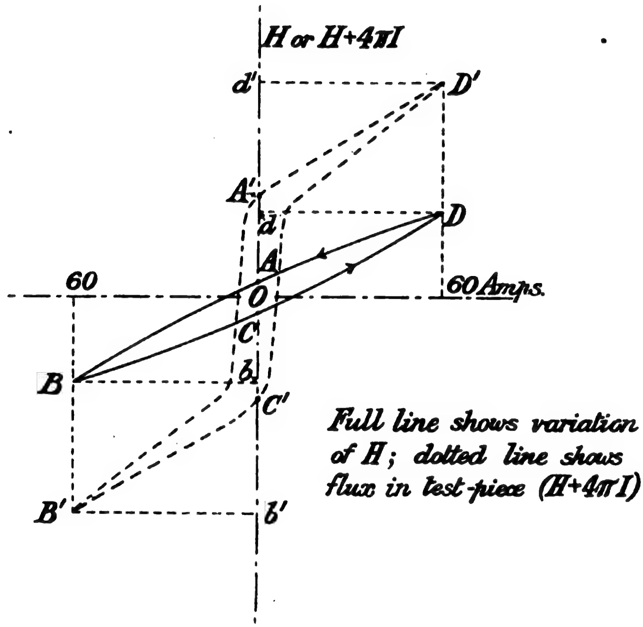


Fig 3.

any moment by taking a fling with the pure iron standard against air, and the magnetisms of the other pieces then reduced to percentages of that of pure iron.

In what follows this magnet will be called the "small" magnet to distinguish it from the "large" magnet described above, with which most of the experiments were made.

The Effect of Field Strength on the Value of I.

The value of I was determined with the large magnet for every one of the alloys in a field of about 8,000 C.G.S., and also in a field of over 20,000 C.G.S. Particulars of these measurements are given later, but

it will be convenient here to give details of some trials which were made with the special object of finding how nearly I could be regarded as constant. These trials may be regarded as typical of all the tests, and the figures (which are given in full) will convey some idea of the order of accuracy attained and of the method of reduction.

It should be explained that when the highest current (60 amperes) was used, the ordinary method of complete reversal was not available because the magnet coils heated too much while the galvanometer needle was being steadied preparatory to reversal. The reversal was

Trial of Low Moor IV. by B H, June 27, 1907.

Nalder galvanometer; period, 15·35 seconds. Constant, $k = 3{\cdot}74 \times 10^{-7}$. Additional resistance, 4 ohms. Total resistance of galvanometer circuit, 8·24 ohms. Galvanometer constant, 198.* Conical pole-pieces, ½ in. apart; current, 60 amperes.

Test-piece.	Fling C′ b′ or C b.	Fling A′ b′ or A b.	Total.	D.
Brass	139½	143	282½	113¾
Iron	140¾	255½	396¼	
Brass	138¾	142½	281¼	115
Iron	140¼	256	396¼	
	Mean value of D			114·6

Value of D corrected for end effects $114{\cdot}6 \times 1{\cdot}16 = 133$.

therefore performed in two parts. Fig 3 shows diagrammatically the cyclical changes of H, and of the flux in the testing coil ($HS' + 4\pi IS$), when it encloses an iron specimen and the current is varied between ∓60 amperes. After two or three preliminary reversals, the current was broken, leaving a residual magnetising force represented by O A. The galvanometer coil was then brought to rest with the circuit closed and the reversing switch thrown over. The current was then made, bringing H to the point B, and the corresponding fling observed. This corresponds to flux change A′ *b′* in the piece. The galvanometer circuit was opened, and the magnet current then broken. This left H at the point C and the test-piece at point C′. The galvanometer was again steadied and the current made again in the same direction (viz., without throwing over the reverser), thus bringing H back to the point B. The fling *b′ d′* corresponding to total

* Viz., the number which, multiplied into the fling gives the total flux embraced by the coil.

reversal is equal to the sum of the separate flings $A'\,b'$ and $C'\,b'$. The difference of the flings is the flux induced in the piece by the residual magnetisation of the magnet, the end corrections cancelling out. When the brass dummy is substituted for the iron piece, the changes of flux in the coil (neglecting end corrections) are represented by the curve $DABC$, and the difference fling D is equal to $b'\,d' - b\,d$.

The observations given on page 247 were taken in fairly quick succession, iron and brass being inserted in the test coil alternately and the pole-pieces not moved.

The flat pole-pieces were now substituted for the conical pole-pieces, and the value of D again determined when a current of 4·9 amperes was reversed. The procedure was the same as before, brass and iron being inserted alternately and the current kept constant within 1 per cent. It is unnecessary to give all the figures. The means were as follows:—

Iron gave a fling of	... ...	212½ divisions.
Brass dummy	... ...	84 "
	D =	128½ divisions

Value of D corrected for end effects 128½ × 1·02 = 131.

The difference between the two values of D is 1½ per cent., and is not more than can be accounted for by errors of observation.

Taking the mean of the two values of D, we have—

$$4\pi I S = \frac{132 \times 396}{2} = 26{,}100 \text{ lines.}$$

The diameter of the piece is 0·316 cm. and the sectional area is 0·0784 sq. cm. Hence—

$$S = 16 \times 0{\cdot}0784 = 1{\cdot}255,$$

and—

$$4\pi I = 20{,}800,$$
$$I = 1{,}658.$$

The area of the coil (S′) is 2·13 sq. cm. The value of the magnetising force with the brass dummy in position with the conical pole pieces and a current of 60 amperes is—

$$H = \frac{282 \times 396}{2 \times 2{\cdot}13} = 26{,}200.$$

The effect of inserting the iron is, as already explained, to reduce this by about 0·09 × $4\pi I$, or, say, 1,900 C.G.S. The actual magnetising force acting on the iron is, therefore, 24,300 C.G.S., and the flux density B is

about 45,000. The force produced by the residual magnetism of the magnet when the current is cut off is—

$$\frac{3\frac{1}{2}}{282} \times 26{,}200 = 325 \text{ C.G.S.},$$

and the value of $4\pi IS$ in this residual field is found by taking the difference of the two flings $A'b'$ and $C'b'$ and subtracting $3\frac{1}{2}$, the corresponding difference with the brass piece. In this case the difference of the flings is $115\frac{1}{2}$, leaving 112 as the fling corresponding to $4\pi IS$ in a field of 325. In this field, therefore, the value of I for this Low Moor iron has reached $\frac{112}{132} = 85$ per cent. of its saturation value. The value of B when $H = 325$ is 18,000, which agrees closely with that found by J. Hopkinson for wrought iron.*

With the flat pole-pieces, H worked out in the same way is about 7,800 C.G.S. This estimate, however, is subject to a correction for the time of growth of flux. More probably H was about 5 per cent. greater than this, or, say, 8,200.

The use of so large a current as 60 amperes is attended with considerable difficulties, and the necessity of making the measurement in two stages greatly increases the probable error. It was therefore given up after all the pieces had been tested by its means, and a current of 30 amperes was used for all further comparisons. With this current it was possible to use complete reversal and the magnetising force H was only about 12 per cent. less than that reached with 60 amperes. It is unnecessary to give the figures of trials made in this way, as they differed in no respect except as regards the pole-pieces and current used from those made with the flat pole-pieces. A very large number of trials were made with different materials, and with one or two exceptions they agreed in showing that the value of D was sensibly the same whether the test were made in a field of 22,000 or one of 5,000 to 8,000 lines. As showing the order of accuracy of these conclusions, reference may be made to a series of determinations made by Mr. Quinney on a piece of nearly pure iron. These measurements were carried out at different times and were all independent, the pole-pieces being shifted occasionally between the tests. Seven determinations of D in a field of about 8,000 C.G.S. (flat pole-pieces 5 amperes) gave a mean of 138·0 scale divisions, the maximum being $138\frac{3}{4}$ and the minimum $137\frac{3}{4}$. Adding 2 per cent. for the end correction, the corrected value of D is 140·9. In seven similar measurements in a field of about 21,000 C.G.S. (conical pole-pieces 30 amperes) the mean value of D was 120·7, the maximum being $121\frac{1}{2}$ and the minimum $119\frac{1}{2}$. The corrected value of *d* given by these tests is $120{\cdot}7 \times 1{\cdot}16 = 140$, which differs by 0·7 per cent. from the other.

Taking due account of the possibility of an error of 1 per cent., arising from the end correction in the high field, we feel justified in

* *Philosophical Transactions*, vol. 176, p. 455, 1885.

concluding that the value of I in nearly pure iron is the same, certainly within 2 per cent. and most probably within 1 per cent., when $H = 21,000$ as it is when $H = 8,000$.

This result receives additional confirmation from a study of the way in which the state of saturation is approached. This is shown in Fig. 4, which refers to pure iron (S.C.I.). The piece was tested between the flat pole-pieces of the larger magnet and with varying magnetising currents and also in the small magnet. The results agree very well, but are affected by the joints at the ends when H falls below 2,000. It will be seen that the change in I when the effect of the joints has been reduced by compression is hardly perceptible until H is less than 1,000. Similar curves, to which reference will be made later, were obtained from a number of other materials. With two or three exceptions, the state of saturation was reached within 1 per cent. at $H = 5,000$.

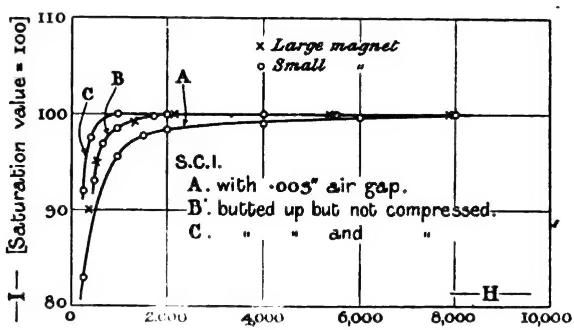


FIG. 4.

THE SATURATION VALUE OF I FOR PURE IRON.

Among the materials available for examination was a sample of Swedish iron (maker's mark, S.C.I.) containing less than 0·2 per cent. of impurities. A special study was made of this specimen with the object of determining the value of I in absolute measure for pure iron. Most of the tests were made on a cylinder of the following dimensions:—

Length	6·26 mm.
Mean diameter at middle	3·18 mm.
Weight	0·385 gramme.
* Density (calculated from weight and dimensions)	7·74

* According to Brown (*Transactions of the Royal Dublin Society*, vol. 9, p. 59, 1907) the density of S.C.I. is 7·877. Our measurements of density depend on estimating the average sectional area of a piece only 3 mm. diameter, which is not easy to measure and may be in error by 1 per cent. The error will generally be in excess because there is a tendency to measure outside diameters, and no account is taken of flats or slight hollows. This, however, is not enough to account for the wide difference, amounting to 2 per cent., between the density here found and the value given by Brown. It is possible that there are local differences of density which may amount to 1 per cent., and which become apparent in these small test-pieces.

A large number of independent measurements of the value of $4\pi I$ were made for this piece in a field of about 8,000 C.G.S. in the manner already described. On each occasion the constant of the galvanometer was determined by means of a standard inductance or a standard condenser. The following table summarises the results of measurements made by three different observers and with the two galvanometers* :—

Observer.	Galvanometer.	$4\pi IS$.
J. H.	Nalder	26,800
B. H.	Broca	26,800 †
H. Q.	Broca	26,800
H. Q.	Nalder	26,600

In the above the end correction of 2 per cent. has been applied to readings of D in all cases. In one test made with the conical pole-pieces in a field of about 21,000 C.G.S., the value found was 26,600. This experiment was made with the Nalder galvanometer, and is in satisfactory agreement with those recorded above for the lower field.

The mean sectional area of this piece is 0·0794 sq. cm. correct within 1 per cent., and S is 16 times the sectional area or 1·270 sq. cm. The mean value of I obtained with the Broca galvanometer is 1,680. and with the Nalder galvanometer 1,675.

A test was also made on another piece of the same iron ⅝ in. long. Flat pole-pieces were used with a current of 10½ amperes, which gave a field of about 7,000 C.G.S. In this case the correction for the ends would be ⅖ of that with the ¼-in. piece, or rather less than 1 per cent. The value of $4\pi IS$ determined with the Broca (long period) galvanometer was 27,000. The dimensions of the piece were :—

Length	15·92 mm.
Mean diameter...	3·19 mm.
Weight	0·99 gramme.
Density (calculated)	7·78

whence the value of I is 1,680.

Finally reference may be made to some experiments made towards the end of the present research by Mr. E. F. Clark, Advanced Student in the Engineering Laboratory, Cambridge. He used a

* The Nalder galvanometer was of suspended coil type, with a period of about 15 seconds; the Broca was suspended magnet and its period was about 30 seconds.

† Mean of four independent measurements, ranging from 26,100 to 26,500.

new magnet with limbs built up of transformer plates and solid pole-pieces having parallel opposed faces 2 in. in diameter. The test-pieces were 1½ in. long by ⅛ in. diameter. The measurements were made differentially, in the same manner as those in the "small" magnet. He used the Nalder galvanometer, and in the circuit was included the secondary coil of a standard inductance, so that a direct calibration independent of resistance measurements, damping, etc., could be performed at any moment by reversing the current in the primary. Using the same Swedish iron in a field of 5,000 C.G.S. he found for four different pieces values ranging from 1,680 to 1,690, the mean being 1,685. The length of the specimen precludes all end effects, the lamination of the magnet eliminates any uncertainty due to eddy currents, and finally the differential method of working and the direct calibration greatly reduce casual errors of observation. On every ground these measurements are to be regarded with considerable confidence, and it is very unlikely that the mean value found by Mr. Clark is in error by so much as 1 per cent.

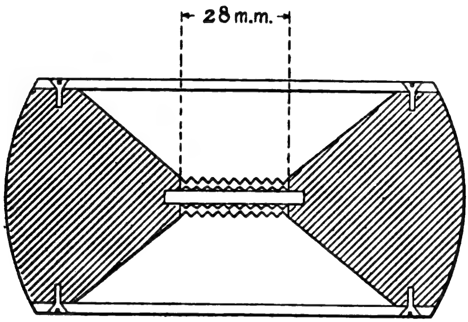
A number of trials were also made on pieces of Low Moor iron, some in absolute measure and some in comparison with the pieces of pure Swedish iron. In most cases the value of I was perceptibly less than for the purer iron, and in none was it perceptibly greater. The difference did not in any case exceed 2 per cent. Mr. E. F. Clark tested five different pieces, and found values ranging from 1,659 to 1,677, the mean being 1,667, or about 1 per cent. less than the value which he found for S.C.I. The following are some values of this constant found by other observers:—

Ewing and Low (Low Moor iron, isthmus method), 1,630–1,740 (mean value 1700).*
Du Bois (optical method H = 2,500), 1,700–1,750.†
Gumlich (isthmus method) (electrolytic iron H = 6,000), 1,725.‡

The last-mentioned determination is the most recent, and it will be seen that it exceeds our value for S.C.I. by 2½ per cent. In part, this may be due to difference in the material. It is quite possible that the density of the electrolytic iron may have been rather greater than that of the S.C.I. which we used. Having regard, however, to the close agreement which we have found between different varieties of nearly pure iron, we think it probable that there is a small systematic error in one or both sets of measurements. Such an error is most likely to occur in the estimation of H. In Gumlich's experiments, as in those of Ewing and Low, the value of H was measured by determining the flux density in an annular air space immediately surrounding the test-piece or isthmus. If the pole-pieces are truncated cones having the same vertex and an angle of about 80°, and if the cylindrical isthmus fills up the whole

* *Philosophical Transactions*, A, vol. 180, p. 242, 1889.
† *Philosophical Magazine*, vol. 29, March, p. 263, 1890.
‡ *Elektrotechnische Zeitschrift*, vol. 30, 1909, p. 1065.

space between the flat ends, then the magnetising force due to magnetism on the conical surfaces is approximately uniform within the isthmus and for a little distance outside it. There will be some magnetism on the cylindrical surface of the isthmus near the ends which, though of small amount, may on account of its close proximity considerably affect the value of H within the piece. Subject to this correction, the amount of which is difficult to estimate, the value of H within the piece will be equal to that measured just outside. Ewing and Low used pole-pieces of the shape described, and it seems probable that in their measurements the field was in fact nearly uniform. The arrangement of Gumlich's pole-pieces and test coil is shown in Fig. 5. The conical poles, though they are of about the correct angle to give a



Diameter of test-piece, 3 mm.

FIG. 5.

uniform field, have not a common vertex, and the field might be far from uniform. The field was explored with test coils when the piece was removed and found to be substantially uniform under these circumstances. But, as we have found in our experiments, exploration of the field when the iron isthmus is removed throws but little light on the distribution when it is there. It is quite possible that the value of H within the piece in these experiments was greater than in the annular space. If this were the case, it would lead to an overestimate of I.

ALLOYS OF IRON: GENERAL.

The following was the course of the systematic testing of the whole series of iron alloys. A test-piece was prepared of each sample about $\frac{1}{8}$ in. diameter and $\frac{1}{4}$ in. long. The value of D for every one of these pieces was measured by Mr. J. Hirst, first with flat pole-pieces and a current of about 5 amperes and then with conical pole-pieces and a current of 60 amperes. The value of H in the first case was about 8,000 C.G.S., and in the second from 24,000 C.G.S. for pure iron to

26,000 C.G.S. for non-magnetic alloys. In the experiments with the conical pole-pieces and a current of 60 amperes the procedure was as described above, the flux-change corresponding to reversal being determined in two parts, by observing the fling on making the current first after reversal and then after breaking without reversal.

In this series of tests the value of H was measured by determining the flux change in the annular space between the concentric coils of bobbin A, which were connected to the galvanometer in opposition. It was at first assumed that the magnetising force in the annulus might be taken as equal to that in the test-piece, but it was found that on this supposition the value of I as obtained by Mr. Hirst with the intense field given by the conical pole-pieces was uniformly less than that found with the flat pole-pieces and a more moderate field. This led to a further investigation of the effect of the ends, the principal results of which are given above. It appeared that the result of taking the magnetising force inside the test-piece as equal to that in the annulus was to cause the value of I to be under-estimated by about 5 per cent. in the tests with conical pole-pieces.

The whole of Mr. Hirst's results were then re-calculated, with proper corrections for the ends. As a result of this re-calculation a close agreement was in most cases established between the saturation value of I obtained in the high and low fields. The following table gives a statistical summary of the results.* The first column shows the number of pieces in which the difference between the high and low field values of I lies within the limits shown by the second column. The difference is expressed as a percentage of the saturation value of I for pure iron, 1 per cent. representing about 16 absolute units :—

Number of Cases.	Difference between High and Low Fields.†
6	exceeding 3 (max. difference 5·4)
7	+2 to +3
9	+1 to +2
5	—1 to +1
9	—2 to —1
1	less than —2 (max. difference —2·3)

The galvanometer fling could be read correct within one division, which corresponded to about 12 absolute units in I or 0·75 per cent. of the saturation value for pure iron. Differences between high and low fields amounting to 1½ per cent. were therefore to be expected occasionally from ordinary errors of observation. Allowing for this it will be seen that there is distinct evidence in a few cases that saturation is not quite reached in the lower field. It is improbable, however, that the difference in any case exceeds 3 per cent. or 50 absolute units.

About 40 of the pieces were then tested by one of us with conical pole-pieces and a current of 30 amperes. With this current complete

* Non-magnetic or nearly non-magnetic alloys are not included.

† Difference reckoned positive when high field exceeds low.

reversal is possible and the measurements are accordingly rather more accurate than those made by Mr. Hirst with 60 amperes. The results in nearly all cases agreed closely with those obtained by Mr. Hirst; where there was any difference it was usually in the direction of a closer approximation to the value found by him in the lower field.

The number of pieces examined by Mr. Hirst was about 100 and covered the whole range of alloys. A considerable number of other pieces were tested subsequently by the other observers. These were mainly iron-carbon and iron-silicon steels which had been subjected to different heat treatments. Finally a large number of pieces were tested differentially in the small magnet, the more magnetic specimens being tested against the pure iron (S.C.I.)* These tests were made in a field of about 13,000 C.G.S. units. Out of over one hundred such tests only four differed by more than two (in the magnetism relative to pure iron taken as 100) from the corresponding results obtained with the large magnet (low field). For the nearly non-magnetic pieces and for those which have nearly the same magnetism as pure iron, these differential results are probably more accurate than the others. A number of magnetisation curves, showing the value of I for different values of H down to about 1,000 were also obtained with this instrument. With regard to these curves it is to be observed that the joints at the ends of the test-piece introduce an error, which may be considerable when H is less than 2,000, the tendency being to make the value of I too low, so that the piece when compared with a non-magnetic material appears to approach the state of saturation more slowly than it does in fact. The amount of this effect in the case of S.C.I. is shown in Fig. 4. So far as possible the piece was of the same length as that with which it was compared, so that there would be no air-gap in either case; but no compression was used. For this reason the curves are not very accurate for lower values of H than 2,000 except in the case of nearly non-magnetic materials, for which the error is inappreciable.

In reducing the results for tabulation the most convenient course is to express the magnetism of each steel in terms of that of an equal weight of pure iron. The difference fling D (corresponding to $4\pi I S$) is determined for the piece, and is compared with the corresponding fling D_0 taken under identical circumstances for a certain standard piece of pure iron. The piece is weighed and its length measured. If W_0 be the weight of the standard and L_0 its length, W and L the corresponding quantities for the test-piece, the relative magnetism of the latter is taken to be $\frac{D}{D_0} \cdot \frac{W_0}{W} \cdot \frac{L}{L_0}$. The lengths of the different pieces are all nearly the same, never differing by more than about 2 per cent. from the mean value. For pieces of equal density $\frac{W}{L}$ is

* Another piece was used for these tests. The density was slightly greater (7·84) than that of the first piece, but the magnetism (when referred to unit of weight so as to correct for the difference of density) was the same within ½ per cent.

a measure of the mean sectional area; where the densities are different it is a measure of mean area multiplied by density. I, the saturation intensity, is generally referred to unit of volume; hence, $\frac{DL}{W}$ is proportional to $\frac{I}{\text{density}}$. It appears to us more logical to express the magnetisation constant in terms of unit mass rather than in terms of unit volume, and it has the practical advantage that the effect of small gas cavities, and to a great extent that of traces of uncombined non-magnetic material such as slag, is automatically discounted. The same procedure was followed by Du Bois in expressing the results obtained by his optical method.

The whole of the results expressed in this way are collected together for convenience in Appendix IV. The analysis and density of each specimen are also shown. The densities were calculated from the weights and dimensions and are expressed in terms of the density of a piece of S.C.I. whose absolute density was 7·84.* The saturation value of I which is given is in each case the most probable value, having regard to all the observations, and is probably in nearly all cases correct within 0·5. Where the high field exceeded the low by more than 2 a note is made of the fact, and the high field result is taken as the true saturation value.

In the same table the results obtained by Barrett, Brown, and Hadfield are also shown. These are put into the form of a statement of the ratio of the permeability of the material to that of pure iron in a field of 45 C.G.S. units, and a statement of the coercive force.

General Conclusions.

Attention may be drawn to the following points of a general character:—

1. There is no alloy having a higher magnetism than has pure iron.
2. Among the alloys there are one or two whose magnetism is greater than the sum of that of their constituents taken separately. Note particularly No. 59, containing 11·4 per cent. Ni.
3. The magnetic properties of every alloy, even those which are practically non-magnetic, are very closely expressed by the relation $B = H + 4\pi I$, where I is the constant which we have called the "magnetism," provided that H exceeds 7,000 C.G.S. The coefficient of H in this equation certainly does not in any case differ from unity by more than 3 per cent. It has sometimes been said that the non-magnetic manganese steels, or some of them, behave as though they had a constant permeability of the order of 1·2 or 1·4. Our experiments are not in accord with this. A steel having a permeability of 1·2 would give the following results:—

$$\text{at } H = 7{,}000, \quad 4\pi I = 1{,}400, \quad I = 112;$$
$$\text{at } H = 2{,}500, \quad 4\pi I = 5{,}000, \quad I = 400;$$

* The smallness of the diameters precludes great accuracy in the measurement of density; the figures given are probably correct within about 1 part in 200.

showing a difference of 288 between the values of I in the high and low fields. According to our experiments on the non-magnetic steels, the difference in the values of I does not in any case exceed 30 units.

It appears that the less-magnetic alloys behave as though they consisted of some substance having a permeability which does not differ

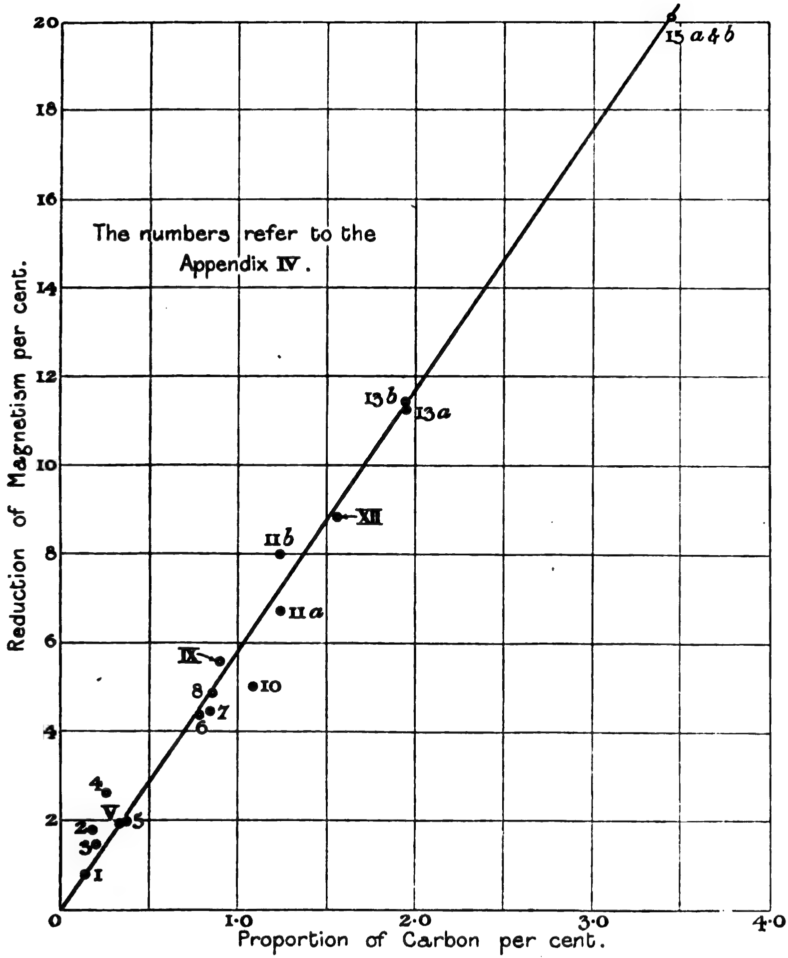


FIG. 6.

from unity by more than 2 or 3 per cent. mixed with varying quantities of magnetic matter which is practically saturated with magnetism in a force of 8,000 C.G.S. Such a mixture would behave in fields of low density as though it had a constant permeability which might greatly

exceed unity. But in fields of high density it would become saturated with magnetism, as the non-magnetic steels are found to do in fact. The curves of magnetisation of steels which are but slightly magnetic confirm this supposition as to the constitution of these bodies. In every instance examined when the magnetism is perceptible at all, it increases much less rapidly than H over the range 2,000 to 12,000. This will be apparent from inspection of the curves Figs. 11 to 16. These curves were all obtained by the differential method and may be relied on as accurate to within one unit (S.C.I. being 100) and within one-half a unit for the nearly non-magnetic materials. For instance, in No. 98 (Fig. 15), whose magnetism relative to iron is about 3 per cent., the value of I in a field of 12,000 is only twice as great as in a field of 2,000.

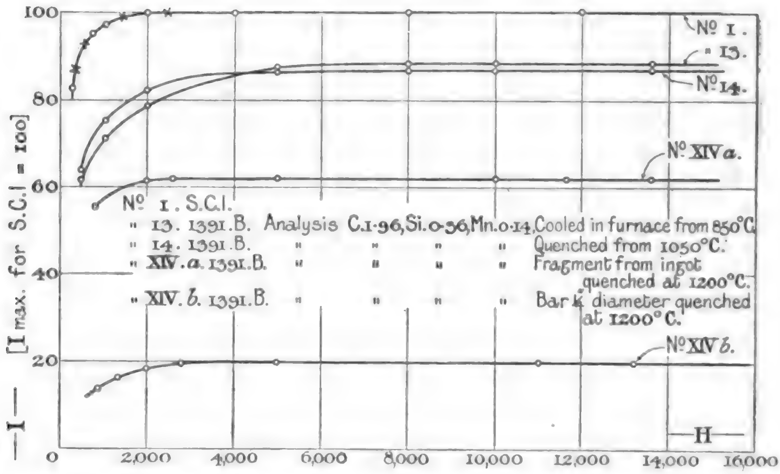


FIG. 7.

4. Comparison with the result obtained by Barrett in fields of 40 units or less shows that in some cases the magnetism of an alloy may be considerably greater relative to that of iron in low than in high fields. Barrett found that several of the silicon steels and one of the aluminium steels were actually more magnetic than pure iron for small values of H; but all these materials are less magnetic than pure iron when saturated. In these cases the coercive force is small. On the other hand, in some alloys with a very high coercive force (*e.g.*, some of the manganese steels) the magnetism relative to pure iron is much greater when saturated than in a field of 40, in some cases more than twice as great.

THE IRON-CARBON STEELS.

Fig. 6 shows the amount of the reduction in the magnetism of iron produced by the addition of varying amounts of carbon. The alloys

shown in this diagram are those containing less than ½ per cent. of substances other than iron and carbon, but the impurities will to some extent mask the effect of the carbon. It is, however, clear that the points are grouped about a straight line. The effect of adding carbon within the limits here shown appears to be to reduce the magnetism by an amount proportional to the amount of carbon, the reduction of magnetism being about six times the amount of carbon. The relation is sufficiently exact to suggest that measurements of magnetism might be used as a means of determining the amount of combined carbon in a steel.

If these steels, all of which were cooled rather slowly, be regarded as mixtures of the carbide of iron Fe_3C and of pure iron, the proportion of carbide of iron will be 15·5 times the proportion of carbon.

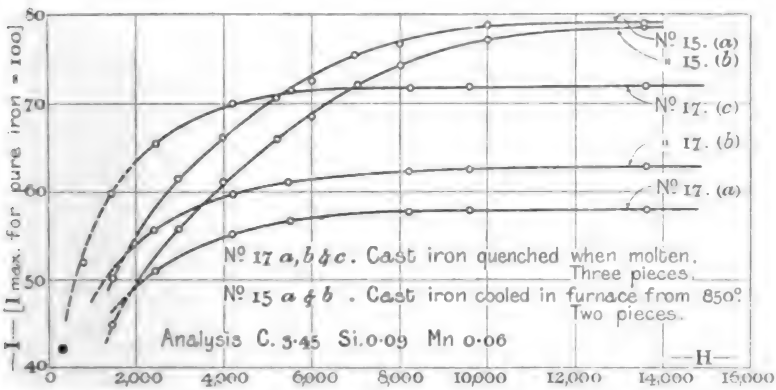


FIG. 8.

Let c be the proportion of carbon in a steel, and let I_0 be the magnetism of pure iron, I_c that of Fe_3C. Then equation (1) connecting the magnetism (I) of the steel with that of its constituents takes the form :—

$$I = 15{\cdot}5\, c\, I_c + (1 - 15{\cdot}5\, c)\, I_0 ;$$

and by experiment—

$$I = I_0 (1 - 6c) ;$$

whence it follows that—

$$I_c = \frac{9{\cdot}5}{15{\cdot}5} I_0 = 0{\cdot}62\, I_0 ;$$

or iron-carbide Fe_3C is about two-thirds as magnetic as pure iron.

The steels containing 2 per cent. of carbon or less are practically saturated at H = 7,000, though No. 13 (1,391 B, $c = 1{\cdot}96$) approaches this state slower than does pure iron. The annealed cast iron No. 15, with 3·45 per cent. Carbon is distinctly short of saturation when H = 7,000, the magnetism being then 75·8, whereas the saturation value of I is 79·7. It is remarkable that if the alloy be quenched in

water from the molten state (No. 17) the resulting product approaches the state of saturation more rapidly and is saturated at H = 7,000, though the value of I obtained is not so high. The same is true of Nos. 13 and 14 (1,391 B).

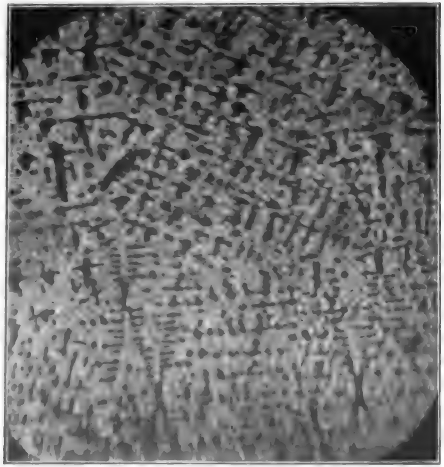
These peculiarities are exhibited in the magnetisation curves Figs. 7 and 8.

Effect of Rapid Cooling.

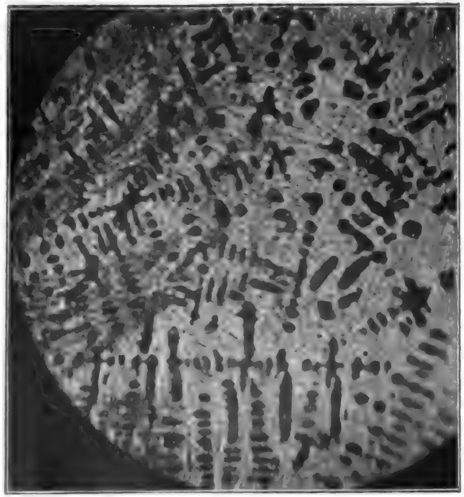
Most of the specimens were allowed to cool slowly in air after rolling or forging. In a few cases special specimens were prepared which had been carefully annealed and allowed to cool very slowly in the furnace from about 850° C. In the carbon and silicon steels little, if any, difference in the magnetism could be detected as the result of this treatment. It may therefore be assumed that the cooling of the original rods was in such cases sufficiently slow to insure the attainment of an equilibrium state.

The effect of quenching was also tried on several pieces. The results appear in the following table :—

No.	Mark.	Percentage of C.	Treatment.	I. Per Cent. of Pure Iron.
8 *a*	1,392 A	0·85	As forged	94·8
8 *b*	"	"	Annealed at 850° C. ...	95·0
9 *a*	"	"	Quenched in water from 775° C.	89·4
9 *b*	"	"	Quenched in water from 775° C.	88·8
9 *c*	"	"	Quenched in water from 1,050° C. ...	88·9
11 *a*	1,392 G	1·23	As forged	93·3
11 *b*	"	"	Annealed at 850° C. ...	91·9
12	"	"	Quenched from 1,050° C.	82·2
13	1,391 B	1·96	Cooled in furnace from 850° C.	88·6 (mean of 2)
14	"	"	Quenched from 1,050° C.	87·8 (mean of 3)
XIV *a*	"	"	Quenched from 1,200° C.	62·0
XIV *b*	"	"	Quenched from 1,200° C.	20·0
15	White Swedish iron	3·45	Cooled in furnace from 850° C.	79·7
16 *a*	"	"	Quenched just after solidifying	76·5
16 *b*	"	"	Quenched just after solidifying (second piece)	75·7
17 *a*	"	"	Quenched molten ...	58·5
17 *b*	"	"	Quenched molten (second piece)... ...	64·0
17 *c*	"	"	Quenched molten (third piece)	72·0



No. 17*a*.
Magnetism, 58·2 per cent.



No. 17*b*.
Magnetism, 64 per cent.

No. 17*c*.
Magnetism, 72 per cent.

Fragments of white Swedish iron quenched when molten × 120.

FIG. 9.

Quenching is, of course, a process of uncertain character, the outer portions of a piece cooling much more rapidly than the inner. This is exemplified in the large differences between the three samples of the cast iron which were quenched when molten. These samples were cut from different parts of the same lump. There are corresponding differences in the micro-structure (see Fig. 9).

Similar results were obtained with 1,391 B (Nos. XIV *a* and XIV *b*). Specimens quenched from 1,050° C. had practically as much magnetism as the annealed piece (88 per cent. of pure iron). In XIV *a*, which was cut from an irregular lump about ¾ in. diameter quenched from 1,200° C., the magnetism was reduced to 60 per cent., while a bar of ¼ in. diameter quenched from 1,200° C. (XIV *b*) had only 20 per cent. of the magnetism of pure iron. Photomicrographs of these three pieces are given for comparison (Fig. 17). The full discussion of these results hardly falls within the scope of this paper, but it may be noted that in this steel, according to the usual theory based on the cooling curves, the formation of cementite would occur in the neighbourhood of 1,100° C. It is possible that the effect of quenching may depend on whether or no free cementite is present, and this might account for the marked difference between the pieces quenched at 1,200° C. and at 1,050° C. respectively. The difference between the two pieces quenched at 1,200° is probably due to difference in the speed of cooling. The second piece (XIV *b*) was the smaller and would cool more rapidly.

Silicon-iron and Aluminium-iron Alloys.

Silicon seems (at high inductions) to act mainly as an inactive diluent, the reduction in magnetism being but little greater than the percentage of this element which is present, after allowance is made for the effect of the carbon. The following figures illustrate this point :—

No.	Si.	C.	Reduction of Magnetism.	Reduction due to Carbon alone.
			Per Cent.	Per Cent.
26 (803)	2·28	0·67	3·6	4·0
29 (898 L)... ...	2·77	0·34	3·2	2·0
28 (898 E)... ...	2·67	0·20	3·9	1·2
32 (898 M) ...	3·03	0·07	4·1	0·4
*34 *a* (1,894 A) ...	3·26	0·15	5·0	0·9
*34 *b* (do. annealed)	3·26	0·15	4·1	0·9
31 (898 K)... ..	3·89	0·11	6·2	0·7
33 *a* (898 H) ...	5·53	0·26	7·4	1·5

In the first two instances in the above table, it would appear that the addition of the silicon had neutralised the effect of the carbon to

* Contains 0·96 per cent. Al.

some extent, the combined effect of the two elements being only slightly more than if both were inert diluents.

Some of these silicon-iron alloys are very soft (magnetically) in fields of low density. Thus No. 28, containing 2·67 Si and 0·20 C, has 98 per cent. of the magnetism of pure iron when $H = 45$ (Barrett), the proportion diminishing to 96 per cent. when saturation is reached. The curve of magnetisation determined by Barrett from this material (Fig. 10) is of such a form relative to that of pure iron as to suggest that the relative magnetism will diminish with increasing force. The

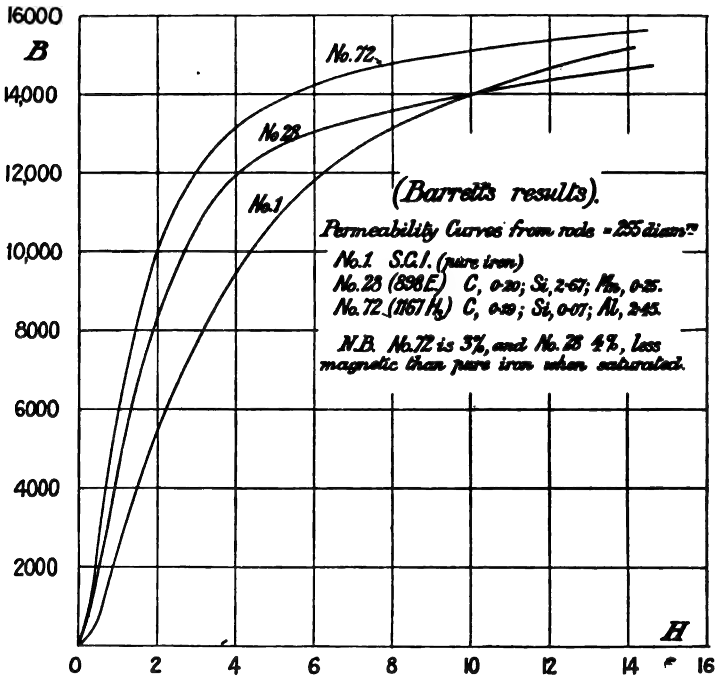


FIG. 10.

coercive force is only about half of that of pure iron. These facts suggest that the silicon has the effect of reducing the interaction of the molecules of iron—perhaps by mechanical separation—without otherwise affecting them. Quenching reduces the magnetism of the silicon-iron alloys, but this may be due to the presence of carbon. No. 33, containing 5·5 per cent. Si and 0·26 C, is hardly altered by quenching, whereas No. 29, containing 2·77 Si and 0·34 C, loses about 3·5 per cent. of its magnetism when quenched.

The effect of aluminium is similar to that of silicon but more marked. Thus No. 72, containing 0·19 per cent. of carbon and 2·45 per cent. of aluminium, has, when saturated, 3 per cent. less mag-

netism than iron. According to Barrett, this alloy is more magnetic than iron in a field of 45 and has a coercive force of 1·0. The permeability curve (see Fig. 10) evidently crosses that of pure iron at some value H greater than 45.

Iron-Manganese Alloys.

We have been unable to discover any simple relation between the proportion of manganese and the corresponding reduction in magnetism. It is well known that the influence of the manganese is greatly affected by comparatively small amounts of carbon. The results which we have found, however, present anomalies which can hardly be explained by the varying proportions of this element. They suggest that there is some other variable, possibly the temperatures to which the alloys happen to have been subjected in rolling or forging, and the precise mechanical character of that process. Thus we have :—

No.	C.	Mn.	Si.	Reduction in Magnetism per Cent.
37 (1,379 B_2)	0·08	3·50	0·130	9·1
38 (1,323 C)	0·15	5·40	0·037	6·4
39 (1,379 D)	0·16	10·08	0·630	55·5
40 (1,379 D_2)	0·15	15·27	—	95·5

In No. 38 the manganese, 5·40 per cent., behaves like an inactive diluent, whereas in 37, containing less carbon, the percentage reduction of magnetism is nearly three times the percentage of manganese. On the other hand, the addition of another 5 per cent. of manganese to No. 38 reduces the magnetism by 50 per cent. Larger proportions of carbon, however, appear to have an opposite effect. Thus No. 42 is only about half as magnetic as pure iron, yet it contains but 3·81 per cent. of manganese. The presence of 0·78 of carbon may be the cause of this. Again, No. 43, though containing more manganese than No. 42, has 91 per cent. of the magnetism of pure iron. In this case the carbon is 0·36. The same thing appears in a comparison of Nos. 47 and 48 :—

No.	C.	Mn.	Specific Magnetism.
47 (1,010 W.T.) ...	1·23	12·64	0
48 (1,338 B_2)	0·26	13·00	15

the higher carbon being associated with the lower magnetism.

A good deal of attention was devoted to No. 47 (1,010 W.T.). This is the original Hadfield's non-magnetic steel, containing about 12 per cent. Mn and 1 per cent. C, and its magnetic properties have been examined by a number of observers, including J. Hopkinson, Ewing, Barrett, and Du Bois. Hopkinson, working in fields of moderate intensity (up to about 200 C.G.S.), found it to possess a constant permeability of about 1·3. Ewing tested it by the isthmus method, and found the permeability to be roughly constant and equal to 1·4 from H = 1,900 to H = 10,000, the value of I in the latter field amounting to about 25 per cent. of the saturation value of pure iron. As Ewing remarks, this is a "respectably high" intensity of magnetisation. Du Bois, using the rotation of the plane of the polarisation of light reflected from the metal as a measure of the intensity of magnetisation, obtained no definite results, the rotation varying with the precise point of the metal surface from which reflection took place. This Du Bois ascribed to heterogeneity of structure.

We have tested in all five pieces of this material, all cut from the same bar, and in none was the magnetism so much as $\frac{1}{100}$ part of that of pure iron. The permeability for H = 10,000 did not exceed 1·02. One of the pieces of this manganese steel (No. 47) was kept for 70 hours at a temperature of 800° C. and then slowly cooled, without, however, making it magnetic. The piece when taken out of the furnace was attracted by a magnet, but after the outer layer (which was probably decarbonised) had been ground off the attraction practically ceased, and the piece then had no magnetic quality perceptible by our method of testing. It is, however, certain that by some sort of heat treatment this steel can be rendered fairly magnetic. A bar is in existence, one end of which has over 27 per cent. of the magnetism of pure iron, while the other end (which had been forged down) is absolutely non-magnetic. The exact treatment to which this bar was subjected is not known, but its composition (C 1·76, Mn 11·6) is nearly that of No. 47 (1,010 W.T.). It will be observed that No. 45 having 1·66 per cent. of C and 11·53 of Mn, had 42 per cent. magnetism, as originally forged. By heating to redness and cooling in air (No. 46), however, the magnetism was completely destroyed. The precise character of the treatment by which it can be restored is now undergoing investigation. It should be observed that both No. 47 in its magnetic state and No. 45 (see Fig. 11) showed steady approach to saturation which was practically reached in a field of about 10,000 C.G.S., like the other materials examined by us. There was nothing approaching the constant permeability found in Ewing's experiments.*

* It may be observed that Ewing's method, though well adapted for examining materials which are nearly as magnetic as iron, is not so suitable for testing non-magnetic alloys. The measurement of I depends on the assumption that the value of H in the neck of the test-piece is equal to that in the outer coil. This assumption of uniformity of field is undoubtedly nearly correct with an iron test-piece. But it is probable that when the test-piece is non-magnetic the force is considerably greater on the axis, than at points at a distance, because of the distribution of magnetism on the end of the conical pole-pieces. This would make the piece, if in the non-magnetic state, appear to have a nearly constant permeability greater than unity,

The magnetisation curves of several different iron-manganese alloys, obtained differentially, are shown in Fig. 11. Our observation that the non-magnetic manganese steel has no perceptible magnetism in fields of high density is, however, consistent with the existence of a nearly constant permeability of 1·3 or 1·4 in fields up to 200 C.G.S., as found by J. Hopkinson. A little pure iron, amounting to, say, 1 per cent. of the whole, if distributed through the alloy in continuous threads, would account for its behaviour both in weak and in strong fields.

The peculiar effects of heat treatment on iron-manganese alloys which appear in our experiments on Nos. 45 and 46 are illustrated by the following results given by J. Hopkinson:—

Steel containing 1·3 *per cent. C and* 8·7 *per cent. Mn.*

As forged ...	... B = 747	in field of	240	units.
Annealed ...	... B = 1,985	„	240	„
Oil-hardened ...	... B = 733	„	240	„

It will be noticed that the cooling in air which presumably followed forging was in this case sufficiently rapid to produce all the effects of quenching in oil. It seems possible that most of the anomalous results obtained from these alloys in this research may be explained by the temperatures to which they have been subjected in rolling or forging. The cooling in air to which all were subjected, and which would be without much effect in an iron-carbon alloy, may have been quick enough in some of these iron-manganese alloys to give the effects of quenching.

In the more magnetic iron-manganese alloys the approach to the state of saturation is very slow in the earlier stages. This is apparent from the magnetisation curves (Fig. 11), and may also be seen by comparing the limiting value of I found in our experiments with Barrett's results for H = 45. Thus No. 43 (4·68 per cent. of manganese, 0·36 per cent. of carbon), is 91 per cent. as magnetic as pure iron in very intense fields, but in a field of 45 units, I for this material is only 49·5 per cent. of its value in pure iron in the same field. Barrett found the coercive force of this alloy to be 19·6 or 10 times that of pure iron, which would lead one to expect excessive magnetic hardness under small forces, though it is consistent with a large saturation intensity. No. 44 has similar properties. In this respect the effect of manganese is opposite to that of silicon. On the other hand, in No. 38 the intensity of magnetisation in a field of 45 units, is 87½ per cent. relative to pure iron, rising to 93½ per cent. under large forces. In this case, however, the coercive force is much less—only 6·0.

One result of the complex effects of temperature or mechanical work on the iron-manganese alloys is that different parts of the same bar frequently exhibit different magnetic qualities. Any statement of the magnetism of these substances ought evidently to be accompanied by a precise specification of the heat treatment. Probably the exact temperature at which rolling or forging took place is an important

factor. Pending further investigation, therefore, in which these details will be noted, the figures given in Appendix IV. for these bodies must be regarded as provisional only.

Iron-nickel Alloys.

The magnetism of the iron-nickel alloys, like that of the iron-manganese alloys, cannot be expressed in simple terms, and is now undergoing further investigation, in which attention is being paid to

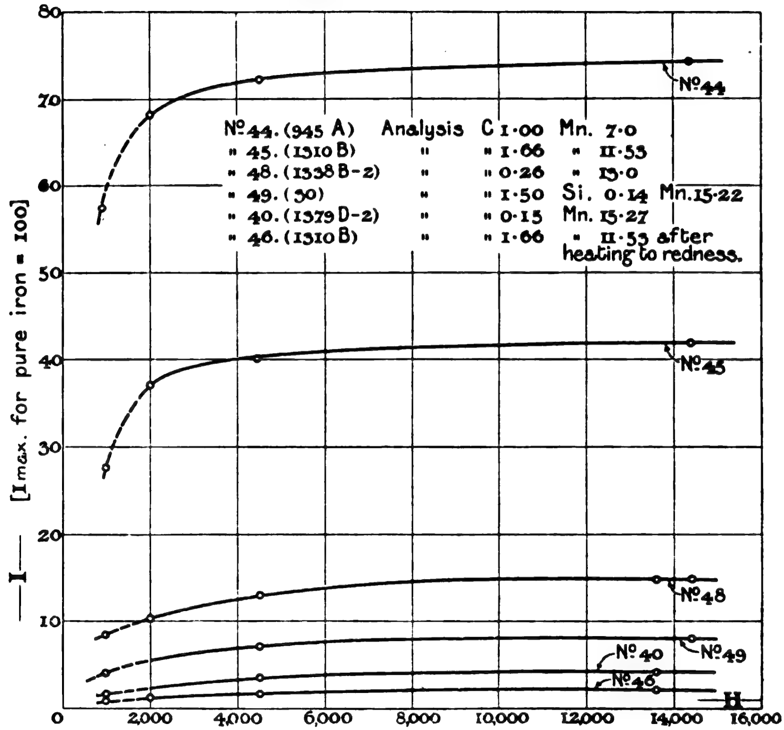


Fig. 11.

various details of heat treatment, etc. Meanwhile, we may draw attention to one or two points which appear in the results already obtained. Comparing the results obtained by us for specimens Nos. 57 to 64 with those found by Barrett for the same materials in fields of low density, it will be seen that in four cases (59 to 62) there is a large increase in relative magnetism when the force is increased from 45 to 5,000. Each of these steels has a high coercive force. The most striking instance is, perhaps, No. 59, containing 11·4 per cent. of nickel, whose magnetism when saturated is 96 per cent. of that of pure iron in spite of the large nickel content, though in a field of 45 it is less

than half as magnetic as pure iron. This steel is remarkable in that its magnetism is greater than that of the elements taken separately.* With the possible exceptions of Nos. 57 and 58 no other alloy in our series possesses this peculiarity. According to Barrett, this material is only half as magnetic as pure iron in a field of 45 units. It will be seen from this that experiments on fields of the order of 100 units may completely fail to reveal the ultimate magnetic constitution of a steel with high coercive force.

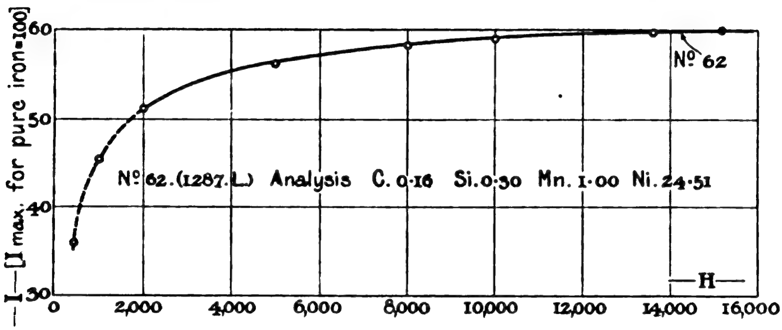
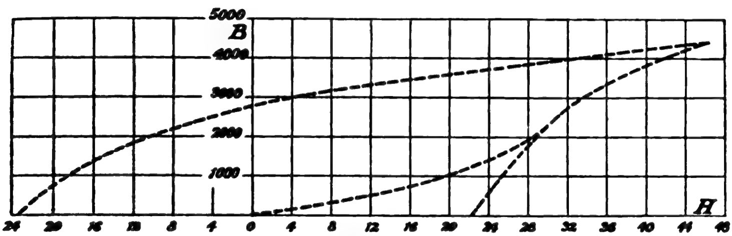


FIG. 12.



(Barrett)
No. 62. (1287 L) C, 0·16; Ni, 24·5; Mn, 1·00,

FIG. 13.

On the other hand, the more magnetic alloys of the group in which the coercive force is low—viz., Nos. 57 and 58—are, relatively to pure iron, practically as magnetic when H = 45 as they are when H = 4,000. The relative permeability of No. 64 (Ni = 31·5 per cent.), which also has a low coercive force, seems to be considerably less in the low field, but there may have been some difference of heat treatment which would account for this.

Fig. 12 is the magnetisation curve of No. 62 (1,287 L), and Fig. 13 is the curve given by Barrett for the same alloy. Fig. 14 is No. 64 (1,449 A). Figs. 15 and 16 show the manner in which nearly non-magnetic alloys approach the state of saturation.

* There is 87 per cent. of iron and 11·4 per cent. of nickel. The nickel is magnetically equivalent to about 3·5 per cent. of iron. Total, 90·5 per cent.

Some of the iron-nickel alloys exhibit the same sort of indefiniteness as regards magnetism as do the alloys of iron and manganese alloys, different parts of the same bar having different magnetic qualities. It is hoped that by further investigation in which careful

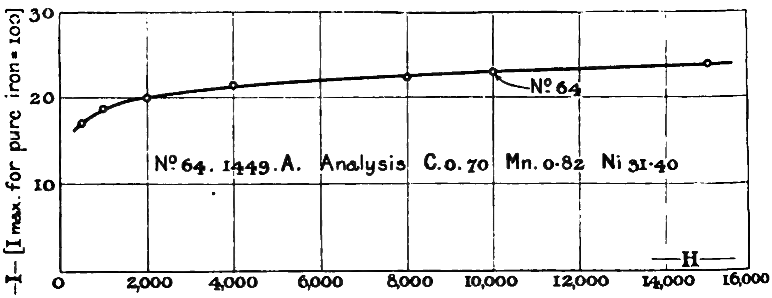


FIG. 14.

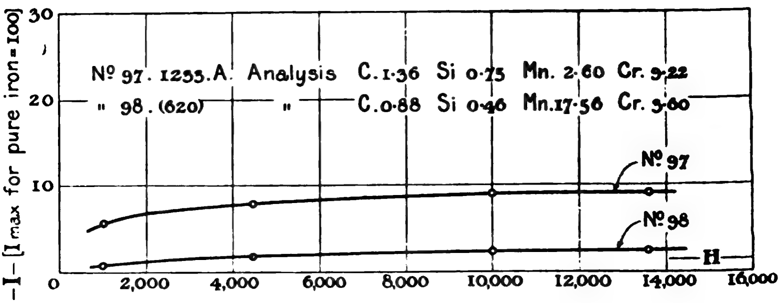


FIG. 15.

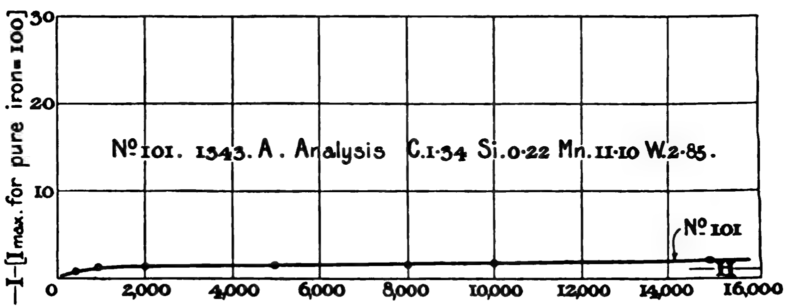
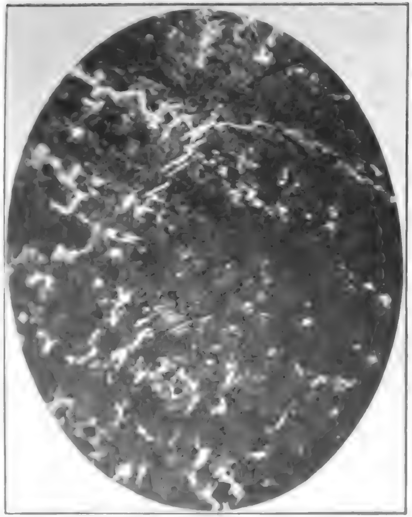


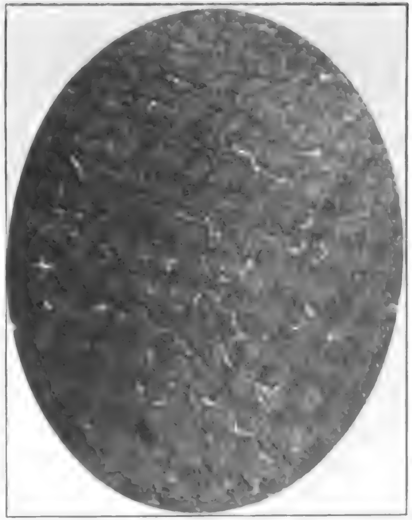
FIG. 16.

observation is kept of the heat treatment this indefiniteness may be removed.

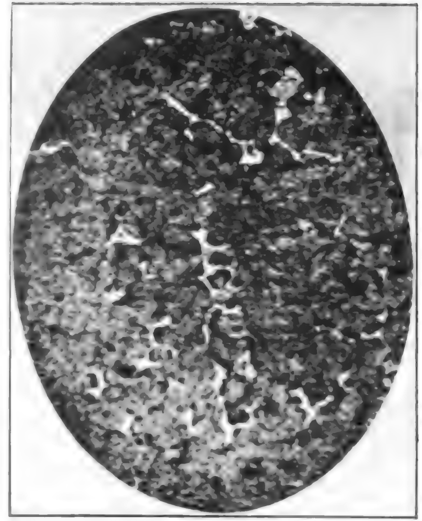
We have to acknowledge with thanks the great assistance which has been rendered in this research by our assistants and by advanced



No. 14.
Quenched from 1,050° C.
Magnetism, 87 per cent.



No. XIV *a*.
Fragment from ingot quenched from 1,200° C.
Magnetism, 62 per cent.



No. XIV *b*.
$\frac{1}{2}$-in. bar quenched from 1,200° C.
Magnetism, 20 per cent.

1,391 B. C, 1·96; Si, 0·36; Mn, 0·14. × 55.

FIG. 17.

students in the Engineering Laboratory, Cambridge, including particularly Mr. J. Hirst and Mr. H. Quinney, and Mr. Milne and Mr. Main, of Hecla Works. The greater part of the laborious work of testing and of reducing the results has been carried out by these gentlemen.

APPENDIX I.

The Ballistic Galvanometer.

The galvanometer used in most of the experiments was of the moving-coil type. This form—though less sensitive than the suspended magnet type—was chosen in order to avoid stray field effects, which are rather large in the neighbourhood of so big a magnet. The galvanometer was made by Nalder Bros., some years ago, and is provided with permanent magnets. It was found necessary to increase the natural period of oscillation considerably, on account of the slowness of the change of flux following a reversal of the magnet current, and, for this purpose, the moving system was loaded with small pieces of lead carried on a mica arm. The period of oscillation was about $15\frac{1}{2}$ seconds, and the resistance of the coil was about 3·3 ohms. The sensitiveness of the galvanometer was such that one division ($\frac{1}{10}$ in.) on a scale distant about 90 cm. from the instrument, corresponded to about $3{\cdot}7 \times 10^{-7}$ coulombs.

In order to obtain flings sufficiently large for accurate reading with the small flux changes available, it was necessary to keep the resistance of the galvanometer circuit low. In most of the tests the external resistance (viz., resistance additional to the galvanometer and testing coil) was 4 ohms, and the total circuit resistance was 8·24 ohms. With this amount of added resistance the ordinary changes of room temperature did not alter the total resistance by more than about $\frac{1}{4}$ per cent. above or below the mean value, and at the same time the sensibility was such that the value of $4\pi I S$ for a piece of Low Moor iron $\frac{1}{8}$ in. diameter corresponded to a fling of about 130 divisions. The damping with so low a resistance was, however, very large, the ratio of successive swings on the same side being 0·331. In the theory of the ballistic galvanometer it can usually be assumed that the damping is so small that its effect on the period of oscillation may be neglected, and in that case the expression for the flux-change F in terms of the fling is $F = k L \phi R \times 10^8$, where k is the equivalent in coulombs of 1 division of undamped fling, R the total resistance of the circuit, and L the fourth root of the ratio of two successive swings on the same side when the galvanometer is freely swinging with its circuit closed. In the present case the damping is so large that the more accurate formula—

$$F = k L' \phi R \times 10^8$$

must be used. k and R have the same meanings as before, and—

$$L' = L e^{-\epsilon \tan \epsilon},$$

where L is, as before, the fourth root of the ratio of two successive swings on the same side, and—

$$\tan \epsilon = \frac{2}{\pi} \log_e L.$$

The following table gives the constant $k\,L'\,R \times 10^8$ (which gives flux-change in the terms of fling) for different values of R, together with the values of L and ϵ on which it is based. It is assumed that $k = 3{\cdot}72 \times 10^{-7}$ coulombs per division, which was the value of this constant for many of the tests.

Additional Resistance (ohms).	R.	L.	ϵ.	L'.	R L' k.
0	4·19	1·757	0·344	1·553	242
4	8·24	1·320	0·176	1·284	394
10	14·22	1·178	0·105	1·168	618
20	24·20	1·108	0·065	1·103	994

The flings produced by the same flux change with different external resistances were carefully compared on a number of occasions, and it was found that their relative amounts were in inverse proportion to R L', certainly within 1 part in 200.

Three methods were used for the determination of the constant k: (1) The discharge of a condenser. A standard condenser with a capacity of 1·015 microfarad was available for this.* (2) By the use of a standard inductance. Two standard fields were used, each consisting of a long solenoid wound on a brass cylinder with a secondary coil of a few turns at the middle of its length. The flux embraced by the secondary coil per ampere of current in the primary was obtained by calculation from the dimensions. (3) By measuring the current a, corresponding to one division of steady deflection on the galvanometer, and calculating the constant from the formula $k = \frac{\tau a}{2\pi}$, where τ is the period of oscillation of that circuit. On one occasion, when all three methods were used, the following values were obtained for k:—

1. Condenser :—

   $3{\cdot}67 \times 10^{-7}$ coulombs per division.

2. Standard fields :—

   (*a*) $3{\cdot}735 \times 10^{-7}$ coulombs per division.

   (*b*) $3{\cdot}745 \times 10^{-7}$ coulombs per division.

3. Steady deflection :—

   $3{\cdot}76 \times 10^{-7}$ coulombs per division.

* "The instrument was marked '1 microfarad,' and the maker's test gave it as 1·0015 microfarad. I am indebted to Mr. Albert Campbell for suggesting that B.A. microfarads were intended and not true microfarads, and thereby clearing up an apparent discrepancy in calibration which had caused much trouble. As the condenser was bought as late as 1906, such a possibility never occurred to me."—B. H.

The period of the galvanometer on this occasion was 15·40 seconds. A day or two later the condenser and steady deflection calibrations were again compared, with the following result :—

Condenser ... ... $k = 3{\cdot}715 \times 10^{-7}$;
Steady deflection ... ... $k = 3{\cdot}715 \times 10^{-7}$.

The period on this day was 15·27 seconds.

The steady deflection method is subject to a little uncertainty on account of the slow change of zero which goes on when the suspension is held twisted.* The most accurate value of k is probably that given by the standard fields, and it has been assumed for the purpose of these experiments that that given by the condenser is for one reason or another ½ per cent. too low. This corresponds to taking $k = 3{\cdot}74 \times 10^{-7}$ coulombs per division in the above group of three tests. It is practically certain that this is within 1 per cent. of the truth, and probable that it is within ½ per cent. The galvanometer constant varied slightly with time, and whenever absolute measurements were desired it was re-determined. The most convenient way of doing this happened to be the use of the condenser, and in all cases ½ per cent. was added to the constant so determined in order to get the correct value. The condenser was always charged to the same potential—about 100 volts—and the potential was measured with the same instrument.

For some tests a galvanometer of the suspended magnet type was used. This was of Broca's form, and was made by the Cambridge Scientific Instrument Company. It had a quartz fibre suspension, and a period of about 30 seconds. The resistance of the coils was about 11·5 ohms. Its sensitiveness was such that it could only be used in a room at some distance from the large electromagnet, and arrangements had to be made for signalling to the operator who reversed the current. On this account the measurements consumed much time, and were only made for the purpose of checking the readings obtained with the other galvanometer. The Broca galvanometer was calibrated by the use of the standard condenser and by the steady deflection method. The quartz fibre suspension made the latter quite reliable in this case. The two methods gave values of k differing by ⅔ per cent., the condenser being the higher.

The ultimate electrical standards used were some Clark and Weston cells which were in close agreement, and a resistance box—by the Cambridge Scientific Instrument Company, which was checked at the National Physical Laboratory. A Siemens millivoltmeter with shunt and series resistances was used for most of the actual measurements of current and potential; its readings were checked and corrected by comparison with the ultimate standards.

* The effect of this was eliminated to a great extent by observing the total fling (sum of right and left) which followed breaking the current in the galvanometer when the latter was deflected. The steady deflection was taken to be half this total fling when corrected for damping.

APPENDIX II.

Slow Growth of Flux in the Large Magnet.

Since the magnet limbs and pole-pieces are solid and of considerable size, the reversal of the current in the coils is followed by the generation of large eddy currents which take some time to die out and delay the change of flux. In order to get a rough estimate of the magnitude of this effect the experiment was tried of reversing the magnet current with the galvanometer circuit open and closing the circuit, by depressing a key, 2 seconds after reversal. The fling of the ballistic galvanometer then corresponds to that fraction of the total flux change which remains to be completed after 2 seconds. The time was roughly estimated by watching a seconds pendulum. It was found that using a current of 5 amperes, obtained from a source of 50 volts, with the flat pole-pieces ¼ in. apart, the fling obtained after 2 seconds was about 5 per cent. of the total observed when the galvanometer circuit was kept closed during the whole period of flux change. Under the same circumstances, but using a source of 100 volts with external resistances, the percentage left after 2 seconds was rather smaller, a result due to the diminished effects of self-induction. These experiments were made with the usual test coil, and with a brass dummy in place of the test-piece.

In order that the ballistic galvanometer may correctly record the flux in a coil connected to it, that change must be completed within a period which is small compared with the period of oscillation of the galvanometer. The latter period in the experiments here described was about 15 seconds, which is longer than usual, but not sufficiently long as compared with the period of the flux-change to preclude the necessity of a careful investigation of the effect of the time of growth of the flux.

A determination of the actual flux in the air-gap was therefore made by withdrawing a coil from the field. The coil used for this purpose was wound in one layer on a circular former about ½ in. in diameter. A large coil was used in order to reduce the effect of the field embraced by the leads. The current (4·9 amperes) was put on with the coil in place between the flat pole-pieces (which were ¼ in. apart), and the coil was then rapidly taken out by hand, removed to a distance of some inches, and placed with its plane parallel to the axis of the magnet poles. The whole operation occupied less than 1 second. The flings observed were 125 divisions with the current in one direction and 127 divisions with the current in the other direction. The flux change produced by reversal, therefore, corresponds to a fling of 252 divisions. The fling actually obtained by reversal of the same current with the coil fixed in place was 235 divisions. Under these circumstances, therefore, the galvanometer underestimates the flux change in the air-gap by 17 divisions, or about 7 per cent. In this test the source of current was a battery of 50 volts E.M.F.; by using 100 volts the error was reduced to about 5 per cent.

With the conical pole-pieces and a large magnet current giving a field of over 20,000 lines, the difference between the values of flux density obtained by withdrawing a coil from the field and by reversing the current with the coil in place, was less than 2 per cent. The smaller difference in this case is doubtless due to the fact that the tips of these pole-pieces very soon become saturated, so that the greater part of the magnetic force in the air-gap develops in a very short time, and only a comparatively small proportion is added after the galvanometer coil has begun to move.

The experiments hitherto described in this section refer to the measurement of H or the field in the air space when no test-piece is there. They show that the errors in the determination of this quantity caused by the slowness of flux change are by no means inappreciable. It happens, however, that these errors do not appreciably affect the determination of I. The reason of this is that the magnetisation of the iron or steel test-piece is almost completely reversed in a very short time. Within less than a second after the reversal of the current the magnetising force has attained a value sufficient almost completely to saturate the test-piece in the reverse direction; and the change in the magnetisation of the test-piece corresponding to the latter parts of the change in H is a very small proportion of the whole. The fling produced by reversing the current with the test-piece in position is made up of two parts, the effects of which can be superposed by simple addition. The first corresponds to $H S'$, the second to $4 \pi I S$. The first part is (apart from end effects) the same both as regards total amount and as regards distribution in time as the flux change when the test-piece is replaced by a brass dummy. It is underestimated to some extent owing to the slow growth of flux, but to the same extent whether the test-piece or dummy be used. The second part, $4 \pi I S$, is the additional flux due to the magnetisation of the steel-piece, and this change is completed in a time so short that the ballistic galvanometer records it correctly. In taking the difference of the flings with and without the test-piece the error in measuring $H S'$ cuts out, and the difference (after allowing for the end correction) gives a correct measure of $4 \pi I S$.

As stated in the text of the paper, the value of I was determined for a number of pieces with another galvanometer having a period of 30 seconds. It was found that the value so obtained agreed within $\frac{1}{2}$ per cent. with that obtained with the shorter-period instrument. The fact that the result is independent of the period of the galvanometer shows that the retardation of the flux is without effect on the measurement of I.

Added February, 1911.

In view of the discrepancy between the value of the magnetism of pure iron obtained in this research and the values of the same constant found by some other observers, it was thought desirable to make a fresh measurement in which any possible effect of reversing the magnet current should be avoided. For this purpose arrangements were made

whereby the test-piece could be withdrawn from the test coil by sliding it in the direction of its length through a hole bored in the pole-piece. A piece of Low Moor iron was used, 1½ in. long by ⅛ in. diameter, and it was placed between the flat parallel pole-faces of the large magnet used by Mr. E. F. Clark, which is referred to on page 252. It was inserted into a brass bobbin wound with a coil of about 70 turns. The coil was connected to a standard inductance and to a ballistic galvanometer. The withdrawal of the test-piece, being equivalent to the substitution of air for the iron within the test-coil, gave a fling which was a direct measure of 4π I S. The exciting current of the magnet was, of course, kept constant during the operation, and the piece was withdrawn just so far that the end was flush with the face of the pole-piece through which it had been drawn.

The value of I found in this way for Low Moor iron was 1,665 in a field of 3,000 C.G.S. units. The same piece tested differentially by the reversal of the exciting current of the magnet gave I equal to 1,656. The difference between the two methods, amounting to about ½ per cent., undoubtedly exists, and is to be ascribed to time lag, but is of no importance for the present research. In a field of 5,000 units the difference would be considerably less.

APPENDIX III.

Calculation of Effect of Ends of Specimens.

It is desired to find the average force parallel to the axis due to distribution of magnetism of uniform density $\pm$ I respectively on the circular ends of the piece.

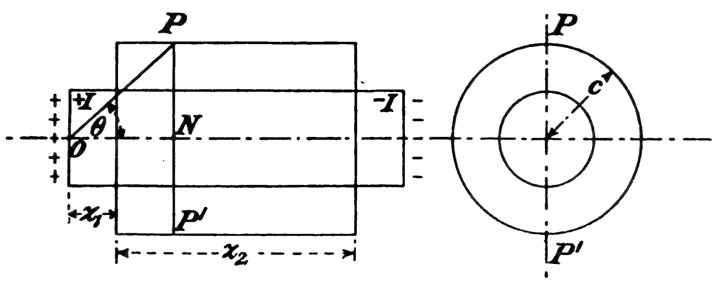


Fig. 18.

The potential of one of the circular patches of magnetism at a point P (Fig. 18) is—

$$V = 2\pi\left[\frac{1}{2}\frac{a^2}{r} - \frac{1.1}{2.4}\frac{a^4}{r^3}P_2 + \frac{1.1.3}{2.4.6}\frac{a^6}{r^5}P_4 - \ldots\right]$$

where a is the radius of the patch, $OP = r$, and P_2, P_4 ... are zonal monics. The total flux from the patch through the circle PP′ (radius c) is—

$$F = \int_1^{\frac{z}{r}} 2\pi r^2 \frac{dV}{dr} d\mu, \quad \text{where } \mu = \cos\theta,\ ON = z$$

$$= 4\pi^2 a^2 \Big[\frac{1}{2}\Big(1 - \frac{z}{r}\Big) + \frac{1 \,.\, 1 \,.\, 3}{2 \,.\, 4} \frac{a^2}{r^2}\Big(\frac{z^3}{2r^3} - \frac{z}{2r}\Big)$$

$$- \frac{1 \,.\, 1 \,.\, 3}{2 \,.\, 4 \,.\, 6} \cdot \frac{5a^4}{r^4}\Big(\frac{7}{8}\frac{z^5}{r^5} - \frac{5}{4}\frac{z^3}{r^3} + \frac{3}{8}\frac{z}{r}\Big) + \ldots\Big].$$

The total flux through a helix of radius c, extending axially from z_1 to z_2, and having n turns per unit of length, is—

$$n\int_{z_1}^{z_2} F \,.\, dz = 4\pi^2 a^2 n \Big[\frac{z - r}{2} + \frac{1 \,.\, 1 \,.\, 3}{2 \,.\, 4} \frac{a^2 c^2}{6 r^3}$$

$$+ \frac{1 \,.\, 1 \,.\, 3 \,.\, 5}{2 \,.\, 4 \,.\, 6} a^4 \Big(\frac{c^4}{8 r^7} - \frac{c^2}{10 r^5}\Big) + \ldots\Big]_{z_1}^{z_2},$$

or, sufficiently nearly, the average flux per turn of the helix is—

$$\frac{4\pi^2 a^2}{z_2 - z_1}\Big[\frac{z - r}{2} + \frac{1}{16}\frac{a^2 c^2}{r^3}\Big]_{z_1}^{z_2}.$$

For coil A (inner coil), we have—

$$z_1 = 0{\cdot}7\,a, \qquad r_1 = 1{\cdot}48\,a, \qquad c = 1{\cdot}3\,a$$
$$z_2 = 3{\cdot}3\,a, \qquad r_2 = 3{\cdot}55\,a,$$

from which it follows that the average flux per turn is $0{\cdot}91 \times 4\pi^2 a^2$. With two end patches of magnetism of density $\pm 0{\cdot}8\,I$, the average flux per turn will be $0{\cdot}182 \times 0{\cdot}8 \times 4\pi IS = 0{\cdot}146 \times 4\pi IS$, S being the area of each patch (πa^2). The difference fling D in this case is therefore reduced by 14·6 per cent. of $4\pi IS$ below what it would be if H were unaffected by the end patches, and the correcting factor is $\frac{1}{0{\cdot}854} = 1{\cdot}17$.

For the outer coil of a the data are—

$$z_1 = 0{\cdot}7\,a, \qquad r_1 = 1{\cdot}885\,a, \qquad c = 1{\cdot}75\,a,$$
$$z_2 = 3{\cdot}3\,a, \qquad r_2 = 3{\cdot}740\,a,$$

whence it follows that the average flux per turn in the outer coil given by patches of density $\pm 0{\cdot}8\,I$ is $0{\cdot}214$ of $4\pi IS$. In the annulus between the coils it is $0{\cdot}214 - 0{\cdot}146 = 0{\cdot}068$ of $4\pi IS$. This is the reduction in the fling due to the annulus, produced by introducing the iron piece. In the experiment described on page 243 the fling corresponding to $4\pi IS$ was 140 divisions, and $0{\cdot}068 \times 140 = 9{\cdot}5$, which is the figure given in the table as the calculated reduction.

For the other coil B the data are—

Inner coil	...	$c = 1{\cdot}11\,a$,	$r_1 = 1{\cdot}31\,a$,	$r_2 = 3{\cdot}48\,a$,
Outer coil	...	$c = 1{\cdot}75\,a$,	$r_1 = 1{\cdot}48\,a$,	$r_2 = 3{\cdot}55\,a$.

And for both coils—

$$z_1 = 0{\cdot}7\,a, \quad z_2 = 3{\cdot}3\,a.$$

The flux in the inner coil due to uniform distributions $\pm 0{\cdot}8\,I$ is 11 per cent. of $4\pi IS$, and in the annulus $10\frac{1}{2}$ per cent.

APPENDIX IV.

The relative density is stated in terms of a piece of S.C.I. whose absolute density calculated from the weight and dimensions was 7·84. The densities given by Brown are in absolute measure, that of S.C.I. being given as 7·877.

The relative magnetism for H = 45 is the ratio of the permeability of the material to that of pure iron in that field, and is calculated from the figures given by Barrett, Brown, and Hadfield.

No.	Maker's Mark.	Analysis. C.	Si.	Mn.	Al.	Other Elements.	Relative Density.	Relative Magnetism (Saturation) Pure Iron = 100.	Relative Magnetism, H=45 (Barrett). Pure Iron = 100.	Coercive Force (Barrett.)	
	IRON.										
I	S.C.I.	0·04	0·07	Trace	—	0·005 S, 0·004 P	1·0000	100·0	—	1·10	
II	L.S.S.	,,	0·02	0·180	—	0·011 S, 0·013 P	0·9860	100·0	—	1·66	
III	B	0·03	0·14	0·036	—	0·016 S, 0·065 P	0·9960	98·6	—	1·66	
IV	Low Moor	—	—	—	—	—	0·9686	98·1	—	—	
IV *a*	Low Moor	—	—	—	—	—	0·9840	98·5	—	—	
	IRON CARBON.										
1	1166 A_4	0·14	0·08	0·07	0·175	—	0·990	99·2	—	—	
2	1754	0·19	0·28	0·52	—	—	0·986	98·2	—	—	
3	48	0·20	0·02	0·50	—	—	0·988	99·5	95·0	3·2	
4	C	0·26	—	1·21	—	—	0·992	97·4	—	—	
5	1397 A	0·37	0·380	0·200	—	—	0·983	98·0	—	—	
V	... ...	0·33	0·037	0·031	—	—	—	96·9	—	—	Annealed at 750° C.
6	1392 H	0·78	0·100	0·100	0·013	—	0·980	95·6	—	—	
7	1392 I	0·83	0·060	0·250	—	—	0·991	95·5	—	—	

8 *a*	1392 A (as forged)	0·85	0·170	0·320	0·020	—	0·984	94·8	—	—	
8 *b*	1392 A (annealed at 850° C.)...	,,	,,	,,	,,	—	0·999	95·0	—	—	
8 *c*	1392 B	0·84	0·200	0·180	0·030	—	0·978	95·1	—	—	
9 *a*	1392 A (quenched at 775° C.)	0·85	0·170	0·320	0·020	—	0·984	89·4	—	—	
9 *b*	1392 B (quenched at 775° C.)	,,	,,	,,	,,	—	0·983	88·8	—	—	
9 *c*	1392 A (quenched at 1,050° C.)	,,	,,	,,	,,	—	,,	88·9	—	—	
IX	... ...	0·91	0·046	0·200	—	—	—	94·4	—	—	Annealed at 750° C.
10	1392 L	1·09	0·170	0·320	—	—	0·985	95·0	—	—	
11 *a*	1392 G (as forged)	1·23	0·120	0·140	0·025	—	,,	93·3	—	—	
11 *b*	1392 G (annealed at 850° C.)...	,,	,,	,,	,,	—	1·000	91·9	—	—	
12	1392 G (quenched from 1,050° C.)	,,	,,	,,	,,	—	0·985	82·2	—	—	
XII	... ...	1·54	0·056	0·057	—	—	—	91·2	—	—	Annealed at 750° C.
13 *a*	1391 B (cooled in furnace from 850° C.)	1·96	0·360	0·140	—	—	0·988	88·7	—	—	
13 *b*	1391 B (cool in furnace from 850° C.)	,,	,,	,,	—	—	0·990	88·4	—	—	
14	1391 B (quenched at 1,050° C.)	,,	,,	,,	—	—	0·984	87·7	—	—	Mean of three pieces, 87·1 to 88·5.
XIV *a*	1391 B (quenched at 1,200° C.)	,,	,,	,,	—	—	0·987	62·0	—	—	Fragment from ingot.
XIV *b*	1391 B (quenched at 1,200° C.)	,,	,,	,,	—	—	0·998	20·0	—	—	¼ in. bar.
15 *a*	White Swedish iron (annealed)	3·45	0·09	0·060	—	—	0·975	79·7	—	—	Magnetism, 75·8 when H = 8,000
15 *b*	Do., second piece	,,	,,	,,	—	—	0·980	,,	—	—	
16 *a*	White Swedish iron (quenched just after solidifying) ...	,,	,,	,,	—	—	0·971	76·5	—	—	
16 *b*	Do., second piece	,,	,,	,,	—	—	0·969	75·7	—	—	
17 *a*	White Swedish iron (quenched when molten)	,,	,,	,,	—	—	0·975	58·2	—	—	
17 *b*	Do., second piece	,,	,,	,,	—	—	0·980	64·0	—	—	
17 *c*	Do., third piece	,,	,,	,,	—	—	0·978	72·0	—	—	

APPENDIX IV.—(*continued*).

No.	Maker's Mark.	Analysis. C.	Analysis. Si.	Analysis. Mn.	Analysis. Al.	Analysis. Other Elements.	Relative Density.	Relative Magnetism (Saturation). Pure Iron = 100.	Relative Magnetism, H=45 (Barrett). Pure iron = 100.	Coercive Force (Barrett).	
	IRON CARBON—*continued.*										
18 *a*	Cast iron (quenched when molten)	4·06	0·04	0·090	—	—	0·955	69·2	—	—	
18 *b*	Do., second piece	”	”	”	—	—	0·894	75·0	—	—	
19	4147/104	0·24	0·59	1·040	—	—	0·979	96·2	92·5	3·40	
20 *a*	6...	0·50	0·65	1·000	—	—	”	97·2	—	—	
20 *b*	6 (second piece)	”	”	”	—	—	0·996	97·0	—	—	
21	611	0·58	0·49	0·580	—	—	0·974	96·6	93·0	2·56	
22	1420 A	0·75	—	1·000	—	—	0·967	94·2	—	—	
23	613	1·05	—	0·580	—	—	0·981	94·1	83·5	6·43	
24	614	1·20	0·46	0·620	—	—	0·980	93·8	”	”	
25	1392 E	1·68	0·13	1·110	0·045	—	0·972	90·5	—	—	
	IRON SILICON.										
26	803	0·67	2·281	0·500	—	—	0·958	96·4	—	—	
27 *a*	803 (quenched at 1,050° C.) ...	”	”	”	—	—	0·954	89·0	—	—	
27 *b*	Do., second piece	”	”	”	—	—	0·958	90·2	—	—	
28	898 E	0·20	2·670	0·250	—	—	0·979	96·1	98·0	0·90	
29 *a*	898 L	0·34	2·770	—	—	—	0·975	96·6	—	—	
29 *b*	898 L (annealed at 800° C.) ...	”	”	—	—	—	0·974	96·8	—	—	
29 *c*	Do., second piece	”	”	—	—	—	0·981	96·9	—	—	
30	898 L (quenched at 1,050° C.)	”	”	—	—	—	0·968	93·0	—	—	
31	898 K	0·11	3·890	0·020	—	—	0·963	93·8	—	—	
32	898 M	0·07	3·030	0·064	—	—	0·977	95·9	—	—	
33 *a*	898 H (as rolled)	0·26	5·530	0·290	—	—	0·965	92·6	95·0	0·85	

33 *b*	898 H (quenched from 1,050° C.)	„	„	„	—	—	0·960	92·0	—	—	
34 *a*	1894 A (as rolled)	0·15	3·260	—	0·96	—	0·977	95·0	—	—	
34 *b*	1894 A (annealed)	„	„	—	„	—	0·979	95·9	—	—	
35	5 per cent. Si iron (cooled in furnace from 850° C.) ...	—	5·080	—	—	—	0·960	80·0	—	—	
36 *a*	5 per cent. Si iron (quenched just after solidifying) ...	—	„	—	—	—	0·892	79·0	—	—	
36 *b*	Do., second piece	—	„	—	—	—	0·877	76·2	—	—	
	Iron Manganese.										
37	1379 B₂	0·08	0·130	3·50	—	—	0·9890	90·9	—	—	
38	1323 C	0·15	0·370	5·40	—	—	0·9960	93·6	—	—	
39	1379 D	0·16	0·630	10·08	—	—	0·9950	44·5	—	—	
40	1379 D₂	0·15	—	15·27	—	—	1·0020	4·5	—	—	
41	53	0·41	0·070	2·23	—	—	0·9850	95·0	87½	6·0	
42	1381	0·78	—	3·81	—	—	0·9640	54·3	—	—	
43	34	0·36	0·100	4·68	—	—	0·9720	91·6	49·5	19·60	
44	945 A	1·00	—	7·00	—	—	0·9850	74·0	23·0	20·00	
45 *a*	1310 B	1·66	—	11·53	—	—	—	42·0	—	—	
45 *b*	Do., second piece	„	—	„	—	—	—	41·5	—	—	
46	1310 B (heated to redness and cooled in air)	„	—	„	—	—	—	2·0	—	—	
47	1010 W.T.	1·23	—	12·64	—	—	1·00	—	—	—	Five pieces tested; all less than $\frac{1}{100}$ of S.C.I.
48	1338 B₂	0·26	—	13·00	—	—	0·9980	15·0	0·7	—	
49	30	1·50	0·14	15·22	—	—	„	8·5	0·8	—	
50	598	1·54	—	18·50	—	—	0·9814	0·0	0·5	—	
	Iron Chromium.										
51	993	0·88	0·19	0·28	—	1·75 Cr	0·980	85·0	—	—	
52 *a*	1177 I	0·43	0·32	0·25	—	3·28 Cr	0·982	93·0	—	—	
52 *b*	1177 I (second piece)... ...	„	„	,	—	„	0·980	„	—	—	
53	1177 N	1·09	0·45	0·10	—	9·55 Cr	0·993	82·5	—	—	

APPENDIX IV.—(*continued*).

No.	Maker's Mark.	Analysis. C.	Si.	Mn.	Al.	Other Elements.	Relative Density.	Relative Magnetism (Saturation). Pure Iron = 100.	Relative Magnetism, H = 45 (Barrett). Pure Iron = 100.	Coercive Force (Barrett).
	IRON NICKEL.									
54	1397 B	0·26	0·33	0·18	—	0·58 Ni	0·990	98·5	—	—
55	1420 B	0·79	—	—	—	0·76 Ni	0·987	93·6	—	—
56	1392 D	0·83	0·18	0·39	—	0·78 Ni	0·980	95·5	—	—
57	1287 D	0·14	0·21	0·72	—	1·92 Ni	0·986	98·0	95½	2·67
58	1287 E	0·19	0·20	0·65	—	3·82 Ni	0·987	98·5	96½	2·76
59	1287 I	0·18	0·22	0·93	—	11·39 Ni	0·991	96·0	48½	17·33
60	1447 B	0·97	0·56	0·61	—	12·08 Ni	0·977	84·3	24·9	22·40
61	1287 K	0·19	0·27	0·93	—	19·64 Ni	0·989	87·8	46·0	20·00
62	1287 L	0·16	0·30	1·00	—	24·51 Ni	0·999	61·0	25·0	22·50
63	1287 L (heated to 550° C. and cooled in air ... ...)	"	"	"	—	"	1·015	"	—	—
64	1449 A	0·70	—	0·82	—	31·40 Ni	1·001	24·0	17·0	0·50
65	1798 H_2 (forged and cooled in air from 550° C.)	0·48	—	1·34	—	19·98 Ni	1·036	0·0	—	—
	IRON TUNGSTEN.									
66	1294 F_1	0·16	0·05	0·11	—	1·10 W	1·006	98·5	95½	3·25
67	1294 H	0·28	0·06	0·28	—	3·40 W	1·009	95·5	93½	5·73
68	1294 I_2	0·38	0·11	0·20	—	7·47 W	1·027	92·5	91·0	9·02
	IRON COPPER.									
69	1264 A	0·68	0·04	0·36	—	1·59 Cu	0·9788	95·3	87·0	5·0
70	1264 B	0·59	0·07	0·32	—	2·49 Cu	0·9935	94·2	85·0	5·4

	IRON MANGANESE COPPER.										
71	1263 C	0·17	0·15	1·04	0·997	2·87 Cu	0·9978	95·1	—	—	
	IRON ALUMINIUM.										
72 a	1167 H_3...	0·19	0·07	—	2·45	—	0·958	97·2	100·5	1·00	
72 b	1167 H_3...	,,	,,	—	,,	—	—	96·5	—	—	
73	1167 D	0·17	0·10	0·18	0·85	—	0·979	97·6	95½	1·80	
74 a	1167 K	0·10	0·11	0·11	2·90	—	0·9430	97·2	—	—	
74 b	1167 K	,,	,,	,,	,,	—	—	96·5	—	—	
	IRON NICKEL COPPER.										
75	1252 B	0·18	0·33	1·10	—	5·81 Ni 2·87 Cu	0·9915	82·2	—	—	
	IRON NI-CR.										
76	1663	0·60	—	—	—	1·96 Ni 2·00 Cr	0·992	82·5	—	—	
77	1286 A	0·25	0·26	0·40	—	2·67 Ni 0·64 Cr	0·981	98·2	90·0	3·0	
78	1480	0·89	0·20	0·14	—	1·92 Ni 2·00 Cr	0·988	89·5	—	—	
79	1286 C	0·31	0·31	0·39	—	2·60 Ni 1·80 Cr	0·990	95·7	90·0	7·9	
80	1775	0·17	—	0·17	—	3·02 Ni 1·55 Cr	0·997	95·0	—	—	
81	1327 C	0·86	0·22	0·60	—	3·22 Ni 1·79 Cr	0·993	87·8	—	—	
82	1734	0·44	—	0·32	—	3·50 Ni 1·71 Cr	0·995	94·2	—	—	
83	1210 D	0·41	0·24	Trace	—	2·60 Ni 4·41 Cr	0·997	92·2	81·0	13·1	
84	1450	0·64	—	0·54	—	12·24 Ni 2·01 Cr	1·004	36·5	—	—	

APPENDIX IV.—(*continued*).

No.	Maker's Mark.	Analysis. C.	Si.	Mn.	Al.	Other Elements.	Relative Density.	Relative Magnetism (Saturation). Pure Iron = 100.	Relative Magnetism, H = 45 (Barrett). Pure Iron = 100.	Coercive Force (Barrett).
	IRON NI-SI.									
85	1103 A	0·38	2·07	0·54	—	3·30 Ni	0·972	95·3	94	2·0
86	1103 C	0·22	3·22	0·80	—	3·53 Ni	0·974	94·3	92½	1·9
	IRON NI-MN.									
87	1254 C	0·57	0·31	3·75	—	3·92 Ni	0·988	79·2	38.0	19·6
88	1287 A	0·19	„	0·79	—	0·27 Ni	0·995	98·8	—	—
89	1267 B	0·78	0·60	1·06	—	4·87 Ni	0·994	90·2	—	—
90 *a*	1339	1·21	—	8·00	—	2·57 Ni	1·015	1·5	—	—
90 *b*	1339	„	—	„	—	„	0·980	1·2	—	—
91	1313 C	1·40	0·70	13·40	—	9·25 Ni	0·997	0·5	0·5	—
92	1109 D	0·60	0·84	5·04	—	14·55 Ni	0·994	„	—	—
93 *a*	1414 A	1·00	—	6·05	—	17·91 Ni	1·017	1·0	—	—
93 *b*	1414 A	„	—	„	—	„	1·007	1·5	—	—
94 *a*	1414 B	1·18	—	„	—	24·30 Ni	1·004	4·5	—	—
94 *b*	1414 B	„	—	„	—	„	1·012	1·5	—	—
	IRON MN-CR.									
95	1274 A	1·14	0·74	4·39	—	4·95 Cr	0·997	2·8	—	—
96	1430	1·30	—	3·09	—	8·92 Cr	0·971	73·5	—	—
97	1233 A	1·13	0·75	2·60	—	9·22 Cr	0·987	8·7	—	—
98 *a*	620	0·88	0·46	17·56	—	3·60 Cr	0·974	3·0	0·4	—
98 *b*	620	„	„	„	—	„	0·995	3·2	—	—

	Iron Mn-W.										
99	687	0·40	0·79	2·28	—	3·20 W	1·008	92·2	91·0	6·1	
100	1234 B	1·28	1·05	1·0	—	7·90 Cr	—	2·0	—	—	
101 *a*	1343 A	1·34	0·22	11·10	—	2·85 W	0·998	3·0	—	—	
101 *b*	1343 A	„	„	„	—	„	1·020	3·2	—	—	
102 *a*	1343 B	1·08	0·51	10·20	—	2·11 W	1·013	0·2	—	—	
102 *b*	1343 B	„	0·50	„	—	„	1·003	„	—	—	
	Iron Mn-Si.										
103	601	0·40	4·27	1·90	—	—	0·954	91·8	—	—	
	Iron Mn-Cu.										
104	1240 I	0·25	0·31	2·01	—	{1·39–1·45 Cu}	0·996	94·7	—	—	
105	1260 A	0·64	0·39	8·06	—	2·65 Cu	1·004	48·9	—	—	
	Iron Cr-Al.										
106	1178 B	0·21	0·22	0·07	0·75	1·69 Cr	0·977	95·2	86½	6·00	
107	1179 B	0·46	0·34	0·18	1·06	3·57 Cr	0·965	91·6	80½	8·00	
108	1178 D	0·18	0·25	0·12	2·40	1·56 Cr	0·957	93·4	83	3·52	
109	1178 E	0·22	0·19	0·08	4·40	1·60 Cr	0·921	91·7	78½	1·77	
	Iron Cr-Si.										
110	518	0·76	1·02	0·29	—	2·11 Cr	0·977	88·2	—	—	
111	517	0·86	1·96	0·40	—	1·96 Cr	1·016	86·2	—	—	
112	1185 F	0·54	2·20	0·22	—	3·50 Cr	0·977	90·2	—	—	
	Iron Cr-Cu										
113	1255 A	0·85	0·31	0·50	—	{1·83 Cu 5·79 Cr}	0·982	86·7	—	—	

APPENDIX IV.—(*continued*).

No.	Maker's Mark.	Analysis. C.	Si.	Mn.	Al.	Other Elements.	Relative Density.	Relative Magnetism (Saturation). Pure Iron = 100.	Relative Magnetism, H=45 (Barrett). Pure Iron = 100.	Coercive Force (Barrett).
	IRON CR-W.									
114	1189 B	0·26	0·05	0·25	—	0·66 Cr, 1·99 W	1·004	94·7	95½	5·30
115	1773 B	0·76	—	0·50	—	2·75 Cr, 20·00 W	1·098	48·7	—	—
	IRON CO-MN-SI.									
116	1209 C	0·25	0·64	1·04	—	1·80 Co	0·978	98·6	98·8	—
117	1209 F	0·52	0·79	0·79	—	6·91 Co	"	98·9	—	—
	IRON NI-MN-CU.									
118 *a*	1424 B	0·83	—	5·90	—	14·44 Ni, 2·25 Cu	1·007	0·7	—	—
118 *b*	1424 B	"	—	"	—	"	1·011	"	—	—
	IRON CR-MN-SI.									
119	608	1·32	1·50	4·23	—	2·02 Cr	0·9762	79·9	—	—
	IRON NI-MN-AL.									
120	1411	0·43	0·61	5·30	2·30	14·10 Ni	0·9615	74·4	—	—

Discussion.

Dr. Silvanus P. Thompson: I am sure we shall all join in congratulating Professor Hopkinson and his absent colleague, Sir Robert Hadfield, on the completion of this elaborate and valuable memoir. We have had more than a hint of further results in hand, and we shall certainly await them with great interest. The results before us go a long way to confirm not only the facts already collected by numerous observers, but the tentative theories put forward by Ewing to account physically for the various facts. One could hardly desire stronger confirmation of that theory in its main outlines than the observations which are now put before us, establishing, as they do clearly, that the saturation value of the intrinsic magnetisation is practically, when high enough, a constant—as it ought to be if Ewing's theory is adequate. I feel inclined to ask Professor Hopkinson whether we might not have a little more statistical matter added to the table, for the length of which he has already apologised. I do not ask him to add to the length, but to the breadth of it. Interesting as these figures are, they do not tell us up to what extreme value the magnetising force was carried. We have been hearing of 5,000, 10,000, and 25,000 as the values of H (values which are unusual for most of us), and I should like to know whether values of that kind were actually applied to these specimens in the tests represented here. Further, I wish there were a column added which gave the ultimate permeability to which these specimens were reduced. We want to find, for example, whether the permeability has come down to less than 2, or to anything like $1\frac{1}{2}$. A constant value of 1·3 was the figure given by the late Dr. John Hopkinson, and 1·4 by Ewing for Hadfield's manganese steel. But that has always been to us more or less of a difficulty. It is very difficult to understand how that steel could be what it was if it had a constant permeability, and did not, like all other varieties of iron or steel, have a diminishing permeability in very high fields. However, the present researches have dispelled the difficulty by showing that those figures were not final, and that now we have to deal with a permeability that diminishes as the flux density is increased; which again compels me to ask, To what figure is that permeability reduced at the extreme case? It is not without interest to know in relation to some of these experiments, because if it be the fact that the permeability of the iron or the steel when pushed very far comes down to a figure between 2 and 1, not differing very greatly from air, then there will be little need for any correction in these specimens, and one might assume that the surfaces of these coned ends respectively on the right and left of the specimen were practically two surfaces of equal magnetic potential, in spite of their being bridged across by the piece of iron. Dr. Silvanus Thompson.

In the results given respecting quenching, the authors frankly say they find difficulty in interpreting the results because they differ in different pieces of the same specimen. They are specimens apparently not sufficiently homogeneous to enable a sound conclusion to be

Dr. Silvanus Thompson.

drawn. I venture to hope they will go on in that inquiry, because it is very important to be able to establish a relation, if there is one, between the magnetic state and the supposed phases of iron when quenching at different temperatures, and to know what that relation is. Metallurgists are talking about alpha and beta and gamma iron, and saying that when it is heated above a certain critical temperature, Ar 2 or Ar 3, the iron changes from alpha to beta or from beta to gamma; but if you quench it suddenly when it has reached one of those stages it retains its particular state. Gamma iron is thus supposed to survive down into the cold temperatures. If it does so it will very shortly be capable of being sorted out from the other constituents by some simple investigation like this. It is a most important point. Professor Hopkinson has told us a very important thing, that every single specimen of iron or steel behaves magnetically as the sum of its separate constituents with their individual behaviours. If there was nothing else than that in the paper, I think we could congratulate the authors and say they had established a very important point. Lastly, I notice that Professor Hopkinson made use of an extremely useful phrase, which we all use in one or another connotation. He spoke of certain specimens being obviously "magnetically hard," apparently because when pushed up into a field of over 2,000 they had not yet become saturated. Does he mean that as a new definition of magnetic "hardness"? Is a substance henceforth to be called magnetically "hard" if it does not attain saturation in any field under 2,000; or, if that is not the definition, what is? I wish to have a numerical distinction as to what is magnetically "hard" and what is "soft," and I think we have cause to ask for it now, because the data are before us.

Mr. Sears.

Mr. J. E. SEARS: I should like to ask the question, whether it has yet been proved up to the hilt that a compound does behave as a mixture. It seems to me there is a possibility, for instance, in the iron-carbon series, that it may not actually behave as a simple mixture of iron and iron carbide would be expected to do. Professor Hopkinson has calculated what would be the magnetism of iron carbide—in a mixture of iron and iron carbide—on the supposition that each is unaffected by the other, but it seems to me that if only one could isolate the iron carbide something quite different might be obtained.

Another question I should like to ask—this is rather a personal matter—is with regard to the iron-nickel specimens. I see the magnetic properties have been investigated up to something like 24 per cent. of nickel. I am rather interested myself in the higher percentages of nickel-iron alloys, and should like to know if any experiment was done on these, and if so with what results.

Mr. Mordey.

Mr. W. M. MORDEY: As you, sir, have called on me I will say a few words, although I must apologise for speaking on this paper without having studied it beforehand. I think we must congratulate ourselves on having a paper of this high quality on this subject and from a son of John Hopkinson—from the successor at Cambridge of Ewing—and in collaboration with Sir Robert Hadfield. The paper is of wide interest.

It appeals as much to physicists, metallurgists, and chemists as to us. I believe this paper will hereafter come to be regarded as of great importance—for the discovery of what is a new physical fact in magnetism: that these materials behave as if they are composed simply of a mixture of magnetic substances with non-magnetic substances. The relation shown in Fig. 6 is very striking. The research and the reasoning seem to me to throw a great deal of light on much that has been obscure in the magnetic action of more or less pure iron. As electrical engineers we are always trying to see how the results of physical research will help towards the practical purposes of the electrical industry. We realise how important such research may be in these matters when we see how in a few years an economical result represented by the yearly saving of many thousands of tons of coal has come out of a previous research, that of Hadfield, Barrett, and Brown, on this same series of iron compounds produced by Hadfield—the paper referred to by the authors. I allude to the reduction of iron losses resulting from the addition of relatively large amounts of silicon, which increased the resistance and reduced the hysteresis. It is interesting to find that, after all, pure iron gives the highest "magnetism." I may, however, point out that for some important purposes pure iron, even if it could be cheaply produced, is not a very satisfactory material, as it "ages" so much—it is very unstable in its hysteresis, and can hardly be touched, or even warmed, without changing for the worse—and its specific resistance is very low. This sensitiveness only applies to its hysteresis; its resistance and permeability seem to be almost constant—certainly they are not much affected by annealing, which may change the hysteresis very much. I would like to be allowed to suggest to the authors a line of further research—an examination of these materials, or others, with a view to finding one with a high permeability at very low values. At medium inductions—say $B = 4{,}000$ to $B = 6{,}000$—we get a permeability approaching or even exceeding 4,000; the maximum is usually at about $B = 5{,}000$. This is not very useful, as such inductions are not much used in practical work. What is wanted for certain purposes, such as the "loading" of telephone or telegraph cables, is a better permeability under very low forces, say less than $\frac{1}{100}$ of a unit. This is perhaps a more hopeful direction than a search for improvement at the higher values. Such a material should have a high specific resistance; its hysteresis should also be low, although that would perhaps be of small importance, as it would probably disappear at the working range of induction. Mr. Mordey.

Mr. W. H. F. MURDOCH: I have only one or two remarks to make, the first regarding equation (1). This equation follows at once from the molecular theory, and it would be interesting to have some data regarding the percentage accuracy obtained in applying it. Concerning the ballistic method of testing, it has always seemed to me that a method where the magnetic fields were reversed absolutely or the specimen reversed is a somewhat unsatisfactory way of testing iron. It appears to me that in that case the iron is being tested under Mr. Murdoch.

Mr. Murdoch.

impulsive forces instead of under a constant H, which is what is more often wanted in practice. Some time ago I made a rough instrument for testing specimens by another method, in which this ballistic change-over method was entirely evaded, and read a paper on it before this Institution, but I have not had time since to perfect it.

Mr. Main.

Mr. S. A. MAIN: I have had the good fortune to be connected with some of the work done by the authors of this joint research, and it has been a great pleasure to me to help in the preparation of the specimens, which have given such important results. I am sorry that Sir Robert Hadfield is unavoidably absent, and am sure that he would have liked very much to have been here. As will be seen in the paper, all the analysis and other chemical tests, the preparation and heat treatment of the many specimens experimented upon, and other work, were carried out at the Hecla Works, Sheffield, the electrical work having been done by Professor Hopkinson.

Mr. Stoney.

Mr. G. STONEY: I think this is a most remarkable paper, and may say it is the second paper we have had on this great series of alloys which Sir Robert Hadfield has prepared. Some years ago we had a most interesting paper by Messrs. Barrett, Brown, and Hadfield on the same subject,* and the value of those researches was pointed out by me among others at the time, and a forecast was given of the commercial value of them. The very low hysteresis obtained from silicon and also from the aluminium alloys was pointed out, and also their high resistances, and in that paper the specific resistance of many of these alloys is given. These alloys, as Mr. Mordey has pointed out, have saved many thousands of tons of coal. There is a further point which is of great interest in these alloys to us as electrical engineers, namely, the non-magnetic ones. I only wish that this research could be further pursued so as to get a non-magnetic alloy which could be machined, and this would give us one thing further, a non-magnetic steel with 35 or 40 tons tensile strength and 30 per cent. elongation, such as could be used for high-speed armatures and rotors. I think it is quite possible and probable that such a material would be cheaper than manganese bronze and more reliable. Professor Hopkinson has given us a hint as to how, possibly, one of these alloys may be made non-magnetic by heat treatment. Will not the same heat treatment give us an alloy which is soft so that it can be machined, and then, by suitable heat treatment, be made non-magnetic? I only hope that this is a line of research which will be pursued.

Professor Morris.

Professor J. T. MORRIS: This paper apparently gives us a real connection between the constitution of a body and the amount of saturation magnetism which can be developed, and that seems a great step in the direction of obtaining a sound theory with which to guide research work in magnetism. On reading this paper, many further pieces of research at once suggest themselves. I should like to ask whether the saturation intensity of nickel and cobalt has been determined, as it would seem to be of importance in connection with the

* *Proceedings of the Institution of Electrical Engineers*, vol. 31, p. 674, 1902.

theory of nickel alloys, more especially as the authors point out the fact that "Among the alloys there are one or two whose magnetism is greater than the sum of that of their constituents taken separately." Further, it has often been noticed that the action of manganese in magnetic affairs is extraordinary, and one has an idea that manganese or some simple combination will some day be found to be a magnetic body. As is well known, its atomic weight is very close to that of the magnetic elements, iron, nickel, and cobalt; and of course it is possible that at very low or high temperatures it might be found to be magnetic. A study of Heusler's magnetic alloy (manganese, copper, and aluminium), which contains no magnetic element, though it acts as a magnetic body, might throw light on the subject. Professor Morris.

With regard to methods of producing high flux densities, my brother, Dr. D. K. Morris, some years ago sketched out an arrangement for getting fields of the value of 20,000 by means of a transformer. The method of testing that he suggested is one in which an alternating current was used. This at once introduces some complications, but at the same time does away with a number of the difficulties which the authors have experienced. Another method would be to employ a large battery supplying an enormous current through a single conductor and to use specimens in the form of little washers threaded on to the conductor, a supply of water being forced through this tube to keep the conductor cool. Professor Hopkinson has told us that he is engaged upon some work on the effect of temperature on the saturation intensity of iron. It would be interesting to know how it varies with temperature, in order to see if the value of the saturation intensity reduces to nothing at the critical temperature of about 780° C. I think it would be of interest if, with regard to the curve given on page 250, some idea of the compression pressure were given, so that we might know whether it is an easy one to obtain practically or not.

Mr. T. HARDING CHURTON: I should like to ask whether any investigation has been made as to the change, if any, in the molecular structure of specimens which have been subjected to reversals of intense fields. The question is suggested to me through having on two or three occasions observed some armature teeth, which had been subjected to a very high flux, break off and adhere to the field-poles after being run for a comparatively short time. Investigation as to the amount of actual pull exerted showed that it was nothing like sufficient to break them off under ordinary conditions. It did not seem to be a question of tensile strength, but rather to suggest that they had become brittle in some way, and possibly that may have been due to molecular action going on under the reversals in the strong field. Mr. Churton.

Mr. W. H. PATCHELL: I might instance as a case of molecular distortion due to electrical influence some bare copper rods used as battery connections at the Maiden Lane Station of the Charing Cross Company. During a fire the switchboard and the supports for the rods were damaged, with the result that the battery was short-circuited. Even where the connections had been out of the influ- Mr. Patchell.

Mr. Patchell.

ence of the fire the rods were found to have become quite short and to have lost their ductility, which, however, could be restored by annealing.

Professor McWilliam.

Professor A. McWilliam (*communicated*): I congratulate the authors on their paper which contains so much valuable material that it is impossible to digest it fully and make proper comparisons in the few days between receiving it and the date of the meeting, and regret that I am unable to be present at the discussion and to take part in it. I would like to mention one point in connection with page 238, No. 5, "Quenching an iron-carbon alloy from a high temperature reduces the specific magnetism by a large but somewhat uncertain amount," and on page 277, XIV *a* and XIV *b*, both of steel 1,391 B containing 1·96 per cent. C, 0·36 per cent. Si, and 0·14 per cent. Mn both quenched at 1,200° C., but XIV *a* a fragment from an ingot and XIV *b* a ½-in. bar; the magnetism of 1,391 B quenched at 1,050° C. is 87·7, of XIV *a* is 62, and of XIV *b* is 20. From considerable experience of the quenching of samples of very varied compositions at different temperatures, I would suggest that, if possible, in every case, but certainly in anomalous cases such as the two last quoted, a careful microscopical examination should be made of the thoroughly polished but *unetched* sample, as often only by this means have we discovered the presence of the finest hair cracks. In some cases we have noted the position of these cracks that were only detected in this way, and on fracturing the sample they were seen to be so fine as to have prevented oxidation. The fracture along the cracked portion was bright and sparkling, and where a part had been so dovetailed in as to break across the solid, the fracture was granular. The composition of 1,391 B is such that one would expect to find such cracks in XIV *a* and XIV *b*. The results on the iron-silicon and iron-aluminium alloys are also specially interesting, as the influence of the large crystals of these alloys as compared with pure iron, does not seem to have the same effect in the strong fields used as compared with the results obtained by Professor Barrett. I am glad to see in such prominence the bar of Sir Robert Hadfield's manganese steel, magnetic at one end and non-magnetic at the other, as I had the privilege of using it in a popular lecture some time ago, when it proved the best appreciated of many illustrations. It will be interesting to know the exact treatment necessary to bring into the magnetic condition such a persistently non-magnetic material.

Mr. Hoyle.

Mr. B. Hoyle (*communicated*): Referring to page 252, the authors state that "The length of the specimen precludes all end effects." The specimen in question had a ratio of length to diameter of 1·5/0·125 or 12 : 1. For open magnetic bars this ratio of length to diameter must be of the order of 500 : 1 before the end effect is inappreciable. Of course this case is very different, because the specimen butts up to pole-pieces, which are 2 in. in diameter, but I should be glad to know how small this ratio of *l* to *d* can safely be made under the conditions mentioned in the paper. Am I right in concluding that the smaller the opposed pole-faces, and the poorer the junction between specimen

and pole-faces, the more marked would be this "end effect" for a given specimen? **Mr. Hoyle.**

Another point occurs in Appendix III., page 275, in the second formula on that page, that is, the one approximately giving the average flux per turn. For substitutional purposes I am not quite clear what z and r are. Is $z = \frac{1}{2} z_2$ and $r = \frac{1}{2}(r_1 + r_2)$? for if so, z must be less than r, and the first term in the bracket is negative and small. The second term in the bracket would seem to come out positive but small also, so that the whole expression appears to come out much less than the value stated, 0·91. I should be glad if the authors would point out my error, if any. (I have taken $2a = \frac{1}{8}$ in. $=$ 0·318 cm.) Lastly, I should like to ask the authors if they would point out some solution to the following: What is the form of the expression for the reluctance of the air-path of an open magnetic circuit core of a solenoid, all the dimensions of which are known; or what amounts to the same thing, what is the flux produced, knowing the B-H curve and ampere-turns and any other data necessary about the core, for which the ratio of length to diameter is such that the effect of the free poles cannot be neglected (say $l : d$ about 10 : 1 or 12 : 1)?

Professor Arnold. Professor J. O. ARNOLD (*communicated*): I have read the paper with great interest, and congratulate the authors on having carried out not only a valuable, but also a suggestive research on a matter of much importance to metallurgists as well as engineers. The authors have found that the permeability of unhardened steels is inversely proportional to the amount of carbon present, "the reduction in magnetism being about six times the amount of carbon," that is to say, 1 per cent. of carbon would cause the reduction of about 6 per cent. in magnetic capacity, whilst 3 per cent. carbon reduced the magnetism about 18 per cent. as compared with pure iron. The authors have thus shown that unhardened steels followed the law which I have previously laid down for hardened steels. This law I suggested in a paper on "The Influence of Carbon on Iron," a fact which has obviously escaped the attention of Professor Hopkinson. My rolled steels ranged in carbon from 0·08 per cent. to 1·47 per cent. carbon, and were rapidly quenched from vacuo at a temperature of 850° C. The bars were then highly magnetised and the tangents of the deflections of the delicate magnetometer were plotted against carbon percentages. A straight line similar to that obtained by the authors for unhardened steels was registered. The tangent for the 0·08 per cent. carbon steel was 0·73323, whilst that for the 1·47 per cent. carbon steel fell to 0·45362; the six intermediate carbons gave results on or near the straight line.*

I wish to suggest to the authors that the falling-off in the magnetic capacity of steels when quenched from very high temperatures is possibly due to minute mechanical water-cracks which I have frequently observed in such circumstances. The cracks always reduced the permeability in a marked manner. It is interesting to note that

* *Proceedings of the Institution of Civil Engineers*, vol. 123, p. 127, 1895.

Professor Arnold.

the micrographs of the three samples of white iron quenched out from a molten condition presented no generic differences in structure, all exhibiting a pale ground mass of cementite overlaid with the normal pearlitic pattern in dark-etching hardenite, nevertheless, the magnetism of these samples varied from 72 to 58·5 per cent. of that of pure iron, the normal sample being 79·7 per cent. I think that each magnetic test-piece should be carefully examined for minute cracks, which might explain the puzzling variations noted by the authors.

Fig. 17 exhibits three micrographs of a quenched wortle steel containing nearly 2 per cent. carbon. These photographs are very significant, because although the steel had been quenched at temperatures varying from 1,050° to 1,200° C., the ground mass in each case is dark-etching hardenite, which is overlaid with various amounts of cementite. So far as I could judge, the central micro-section exhibited hardening cracks. I suggest that it would be well to remedy a slight oversight in the paper by substituting the word "photomicrograph" for "microphotograph." As a metallurgist, I regret that so much valuable laborious work like that of Madame Curie should have been carried out without metallurgical advice. It is most important that magnetic test-bars should have the chemical composition attributed to them and that their micrographic features be identical throughout. Rolled bars nearly always have a more or less deeply decarbonised skin which would upset any reliable correlation of the magnetic properties of the bars with their chemical composition.

Mr. Osmond.

Mr. F. OSMOND (*communicated*): The authors' paper is of very great importance; it does not solve the question of temper in steel, but it shows it in a new light, and, in consequence, opens up a new field for research.

The idea of searching for a method of quantitatively determining the proportion of magnetic iron in a given alloy is an excellent one. Former results comparing the magnetic properties of an annealed alloy with those of the same steel, but tempered, appear to leave, in the tempered metal, plenty of room for the magnetic varieties of iron; but since very intense fields, relatively to the samples, were not employed, we might ask what would become of this discrepancy in much more intense fields: the authors' experiments show that this discrepancy is actually much reduced.

Therefore, if we leave aside the austenitic steels for which the allotropic theories have been confirmed, and if we suppose that magnetisable iron is the same thing as crystallised alpha iron, and if we admit, as we may do in the case of a metallurgist like Sir Robert Hadfield, that every precaution was taken to avoid decarburisation in the heating of the small samples and to ensure that they were normally tempered, it can be taken as established that in the martensite of a eutectoid steel (specimens 9*m*, 9*b*, 9*c*), the proportion of non-alpha iron cannot exceed in round figures 5 per cent.

This is very little; and the position from the standpoint of the

allotropic theory, which ascribes the properties of martensite as being due to beta iron, appears for this main reason to be rendered untenable. On the other hand, it seems to be definitely proved that carbon is not the direct cause of temper. To the ancient arguments which supported this view there has in recent years been added one which appears decisive. Mr. Osmond.

M. Maurer has in fact shown that during the reheating of austenite, in proportion as the resistivity decreases—a phenomenon which corresponds to the separation of carbon in the form of cementite—the hardness, in place of diminishing, actually goes on increasing. And this hypothesis leaves hardly any other hypothesis, for explaining the phenomenon of temper, than that of a particular state of the iron.

Put briefly, in view of the results obtained by the authors, not a single theory of the phenomenon of temper would remain standing unless it underwent certain modifications.

The modifications which one could propose are naturally of a hypothetical nature, but it is interesting, none the less, to examine them, even were it only to stimulate further research.

At the moment I can see three hypotheses which would reconcile the facts with theory:

1. The steel de-tempers itself in intense fields. This hypothesis is, however, exceedingly unlikely, and a verification as to whether the tempered specimen preserves its hardness under the file when subjected to the action of the maximum field would doubtless suffice to dismiss it once for all.

2. We can suppose that the kind of iron which is the cause of the hardness of tempered steel is not beta iron, but amorphous alpha iron. The alpha iron would remain amorphous, or something approaching that state, because the great rapidity of cooling and the existence of passive resistances due to the presence of carbon do not allow recrystallisation, the natural sequence of an allotropic transformation, to take place.

3. Beta iron has a magnetic form, in addition to its known non-magnetic form. This hypothesis has already been put forward under other circumstances by Professor C. Benedicks. It agrees sufficiently well with the views of Professor Weiss, of Zurich, who distinguishes beta iron from alpha iron by a different mode of motion of the molecules, and not by a transformation of the molecule itself, which remains magnetic in both cases. If this be so, we can conceive that this molecule, magnetic, but not magnetisable between the points A_3 and A_2, would become magnetisable at a lower temperature, without its mode of motion being changed. In support of this hypothesis we could perhaps again invoke the duplication of the A_2 point, which I first pointed out in certain specimens and which has also been observed by other experimenters.

In conclusion, I hope that these notes, which have been suggested by the authors' remarkable work, may lead to some new and interesting researches.

Professor Heyn.

Professor E. HEYN (*communicated*): The magnetic investigation is able to shed new light on various questions in scientific metallurgy which are in urgent need of explanation. The authors' paper is of great interest, as it marks substantial advances in this direction. It enunciates in a clear manner several laws on the relation between the mass of constituents of iron-carbon alloys and their magnetic properties, and it may be expected that the promised continuation of the investigations, due to the fortunate collaboration of the experienced metallurgist with the experienced physicist, will, in addition, shed further light on the complicated relations in manganese and nickel steels.

Professor Knowlton.

Professor A. A. KNOWLTON (*the University of Utah, Salt Lake City*) (*communicated*): I wish first to congratulate the authors upon the excellence of their methods and the degree of accuracy apparently attained. The very thorough investigation of the precautions and corrections necessary for the estimation of the true value of H within the test-piece will be of service to every worker in this field. The intrinsic value of the experimental results is large, and I have found the paper unusually suggestive of starting-points for further investigations, some of which should lead into quite new fields. The conclusion, suggested by the experiments upon the effects of carbon, that cementite is about two-thirds as magnetic as pure iron, is a case in point. An extended study along this line with the aid of thermal and microscopic analysis should be undertaken at an early date. It is possible that the effect of silicon and aluminium in partially neutralising the action of the carbon, as shown, may be due to the formation of carbides of these metals, thus reducing the amount of Fe_3C, and leaving proportionately more pure iron in the binary alloy. On the other hand, this decrease in cementite (if such a decrease occurs) may be related to the well-known tendency of these metals to diminish under cooling so that a greater amount of hardening carbon, and hence also of pure iron, might be found in those specimens whose magnetic properties vary most from simple additive effects. In any case, the irregularities observed in the amount of this neutralising effect are doubtless due to differences in the thermal history of the specimens, and the investigation of the causes which produce them can hardly fail to lead to important results. Dr. L. A. Bauer has recently pointed out in connection with terrestrial magnetism that "A long step forward will have been taken towards the solution of the origin of the earth's magnetism when once we have found out what causes it to vary,"* and the statement applies equally well to magnetism in general.

The simplicity of the effects due to carbon, silicon, and aluminium is in strong contrast with the complicated and irregular action of the manganese and nickel steels. The known tendency of manganese to increase under-cooling (opposite to the effect of silicon) is not apparently a sufficient cause for variations of the magnitude observed. It is worth while to recall that manganese alloyed with Al, Sb, or As

* *Science*, vol. 32, p. 41, 1911.

becomes ferro-magnetic, and that iron is in its trivalent form closely allied with these elements. I have shown * that the magnetism of the Heusler alloys appears to be localised in a certain type of crystals which are very sensitive to heat treatment. The behaviour of the Hadfield manganese steels is sufficiently analogous to make it probable that a like explanation of their variation may be found. Professor Knowlton.

It is of great importance when working with alloys showing such irregularities—and I believe this applies in some degree to all magnetic alloys—to have a complete thermal history of every specimen. Rolling and forging with the accompanying uncertainties of heat-treatment should be avoided whenever possible. This is of special importance in the case of steels like these, where it is possible that some of the changes due to thermal treatment may be irreversible. What seems clear from the experimental results is that the manganese affects the magnetism of iron in a much more fundamental way than do carbon, silicon, and aluminium. I think it likely that in the first case the magnetism of the pure iron itself is altogether unaffected by the presence of the alloying impurities except as these reduce the amount of iron per unit volume, and change the hysteresis relations by changing the purely mechanical constraints which the non-magnetic molecular groups impose upon their magnetic neighbours. The assumption of such mechanical constraints in addition to the magnetic constraints due to the mutual interaction of the magnetic groups themselves, simplifies somewhat the interpretation of such peculiar results as that the magnetism of silicon and aluminium steels is relatively higher, compared with that of pure iron, in weak and medium fields than in intense fields, while the reverse is true for manganese and nickel steels. In the case of the latter steels, it seems probable that the alloying metal takes part with the iron in the formation of complex molecular groups which are the magnetic units and that the magnetic moment of the group itself, as well as its relations to surrounding groups, depends upon the precise nature of the structural elements of a series of mixed crystals.

Sir Robert Hadfield. Sir ROBERT HADFIELD, F.R.S. (*communicated*) : I should like to express my great admiration of the very valuable and exhaustive work which has been dealt with in his share of this research by my colleague Professor Hopkinson. Too much praise cannot be given for the way in which he has carried out the long series of electrical tests described and extending over several years.

Professor Hopkinson has asked me to make a few comments to add to the discussion, but he has done his work so completely that from the electrical side there is little left to be said.

As I have not at the moment before me the various remarks made by those present when the paper was read, I do not know exactly what line was taken up during the discussion, or what were the exact questions asked.

As regards my part of the work, I may say that a careful selection was made of the most interesting specimens, representing experiments

* *Physical Review*, vol. 32, p. 1, 1911.

Sir Robert Hadfield.

covering twenty years or more. Some of these steels, if they had been made with the ferro-alloys now readily available, which are lower in carbon percentage, might have given resulting steels also somewhat lower in this element, that is, there would have been less disturbance from the carbon present. Still on the whole the steels largely represent what could be produced even to-day, and may be relied upon as representing the qualities of these particular steels having the analyses stated.

I understand Mr. Mordey, whose long experience in various special branches of electrical work entitles his comments to special consideration, has stated that it is very desirable to increase the permeability values of certain iron alloys at high densities. In the many experiments I have made during the last few years, this point has not been lost sight of, but so far entire success has not been met with. My own feeling is, too, that until we know more about the behaviour of *pure iron* itself under varying physical conditions and at different temperatures, as well as having as an aid electrical tests of better and more reliable nature than those now in use, for which perhaps the apparatus has not yet even been invented, we shall not effect any great improvement in the qualities of iron and its alloys in the way desired. In a number of cases which have come before me, magnetic testing is not at all in a satisfactory condition. For example, in determining "total losses," specimens giving higher resistance, and which should have had lower eddy current losses, have not shown these. Moreover, at the present time, in such tests it is often difficult to get two laboratory results in agreement when tested with different apparatus. This remark also applies to hysteresis losses. We metallurgists, therefore, look to the electrician to help us in this respect.

The purer the metal iron is, the higher its permeability when properly heat treated, and as all added elements to iron are more or less impurities so to speak, it hardly seems possible to reach the desired result of improved permeability with an alloy steel. Possibly better knowledge of iron itself and special heat treatment may lead to improvements, but then if one quality is improved, others may be lost. For example, permeability might be increased but electrical resistance lessened, which would make the product less valuable for certain electrical work.

In any case I think it may be said that without doubt this research has given important new facts for consideration. To have proved, as the tests carried out by Professor Hopkinson do, that at the present time there is no known iron alloy possessing higher magnetism than pure iron itself, is in itself a valuable contribution to the general store of knowledge on this question.

As regards the magnetic and non-magnetic conditions of the various alloys, these represent a very large field for investigation. In a recent contribution to a technical society on another matter I have pointed out that with regard to the varying qualities of these peculiar alloys, for example such an alloy as "manganese steel," we want

much more light upon the subject before we can dogmatise. Our knowledge is not as great as it should be, and I hope Professor Hopkinson will continue important researches he has in hand in this direction, one of which is to investigate the saturation intensity of magnetism at high temperatures. Sir Robert Hadfield.

In contributing to the discussion on a recent paper by McCance * on "The Constitution of Troostite and the Tempering of Steel," I have referred to some of the peculiarities in non-magnetic iron alloys. Perhaps it may be also interesting and useful to refer to them here, as, if we can accurately define the nature of these peculiar properties such a result would greatly help to a correct understanding and study of the various phenomena, specially electrical, presented and met with in the joint paper by Professor Hopkinson and myself. By following up the line of thought from the new point of view suggested and set forth by Professor A. A. Knowlton, of the University of Utah, in his paper on "The Present State of our Knowledge of Magnetic Materials," † perhaps light may be thrown upon electrical problems where these concern the use of special varieties or alloys of iron with other elements, or even of the metal iron itself. Seeing that the work of the electrician largely relates to the use and behaviour of the metal iron, Professor Knowlton's statement that he considers ferro-magnetism to be undoubtedly neither atomic nor molecular, but crystalline, seems worthy of very careful consideration. I hope we may before long induce him to read a paper on the subject before some of our British Societies.

As my citation of Professor Knowlton's paper has arisen upon and from the discussion of Mr. McCance's paper, and as my comments on this paper also appear apposite to the facts dealt with in this joint paper by Professor Hopkinson and myself, it seems advisable to quote somewhat fully from these papers. Moreover, the points to which I refer seem to also bear more or less upon the problems to be considered by the electrical engineer when he asks for more information with regard to the qualities of the metal iron, and whether further discoveries may be expected regarding its treatment and improvement. As I have said, further advance can probably only now occur by the united efforts of the metallurgist and the electrician.

Speaking now of the paper by Mr. McCance, as many members of this Institution are aware, much discussion has taken place as to whether the metal iron can exist in more than one condition. There are those who think the metal iron is allotropic, though the writer does not think so as to a hard adamantine form of iron. In any case he cannot go so far as those who already claim four distinct forms of iron : alpha, beta, gamma and delta. The writer thinks the existence of such forms has not been proved, and he would much prefer to look for the explanation of the many peculiar problems met with in iron and its

* *Proceedings of the Institution of Mechanical Engineers*, December, 1910.

† *Terrestrial Magnetism and Atmospheric Electricity*, vol. 15, p. 3, 1910.

Sir Robert Hadfield.

alloys to the suggestions so ably set forth by Professor Knowlton, who considers that the properties of the magnetic alloys known as "Heusler's" are due to a certain crystalline structure, which at present we do not understand, and that atomic susceptibility varies in relation to the ordinary or mass susceptibility. This explanation would apply to ferro-magnetic alloys generally. Professor Knowlton also states that ferro-magnetism must in his opinion be associated with some peculiar grouping of the ultimate particles (molecules in the chemical sense) of the material, whether it is an element like iron or a mixture as in the Heusler alloys. He also adds that he considers the phenomena of hysteresis are on the other hand probably due, in part at least, to the nature of the matrix surrounding the magnetic elements and to the constraints which this matrix exerts upon these magnetic groups. He further adds that a comprehensive working hypothesis as to the precise nature of this structure is the greatest present need it this field. I have quoted Professor Knowlton's remarks very fully as they seem to be of the greatest importance. As will be seen from certain remarks now quoted, a line of thought probably running in a similar direction is indicated by the eminent French scientist, M. H. le Chatelier.

I add my remarks upon the paper by Mr. McCance previously referred to, and read before the Institution of Mechanical Engineers,* as they may interest electrical engineers who are studying this subject. He there states: "Beta iron is known to be non-magnetic." It is doubtful whether any definite facts are yet available that beta iron exists at all, and the fact that iron is non-magnetic beyond certain temperatures can hardly be claimed as proof of allotropic modifications, and still less as a proof of the existence of adamantine beta form of iron, which the expression "beta iron" really implies.

Moreover, surely the changes produced in molecular constitution are not those coming at all under the head of allotropy, that is using the term in its original meaning, because all matter is more or less subject to changes in molecular constitution by temperature variations, yet one does not speak of these as allotropic modifications. Therefore the fact that iron becomes non-magnetic by heating would hardly seem to be any real proof of the existence of an allotropic beta form, any more than the fact that the iron present in manganese steel, which is practically non-magnetic at ordinary temperatures, owes its non-magnetic qualities to the so-called beta form of iron. This latter point is specially important, because manganese steel being very hard under the tool cannot be machined, but is absolutely different in its hardness as compared with hardened carbon steel. The Brinell ball hardness number of manganese steel is only about 200, whereas that of ordinary carbon steel hardened varies from 700 to 850. Whilst above a point in temperature which may be termed for convenience B—which must not, however, be taken to have the

* *Proceedings of the Institution of Mechanical Engineers*, December, 1910.

Sir Robert Hadfield.

same significance as the term beta as hitherto employed—there is a modification in what may be termed the molecular constitution of iron; this also occurs below this point B. Iron, like many other metals, shows considerable difference in its molecular constitution with the rise or fall of temperature. In other words, its condition is not stable any more than other bodies. The use of the terms A and B, as they do not carry a "biassed significance," as designating some differences, would therefore be much more satisfactory, until facts are proved to the contrary, than the use of the terms α and β by the allotropists. That such forms of iron exist has not yet been proved.

M. Grenet in his excellent paper on "La Transformation de l'Acier dans les Limites de Temperature" has adopted a similar way of describing the changes produced by variations in temperature. He terms them "conditions of stability," condition C (or as above, B) being the stability when cold, and condition H (or as above, A) being the stability when hot. Moreover, he points out when studying the iron and carbon alloys that no "distinction should be made between the changes in the condition of the iron and the dissolution of the iron into a solid solution, since both are one and the same thing." This valuable paper by M. Grenet has not yet, I think, appeared in any English technical journal. It would be of great service if M. Grenet would give us a paper similar to that which appeared in the *Bulletin et Comptes Rendus Mensuels de la Société de l'Industrie Minérale* for August, 1910. It is true that so-called gamma iron, another allotropic form of iron, is stated to exist, but as iron itself becomes non-magnetic upon reaching about 750° C., and the gamma form is not supposed to occur until after a temperature of about 850° C. is exceeded, it hardly seems that this bears on the particular point now under consideration.

It seems to be commonly accepted that all our metallurgical friends in France are allotropists in the sense I understand Mr. McCance claims. However, this is not so, as M. H. le Chatelier, whose long experience and great ability as a scientist in metallurgical as well as other matters is well known, has himself pointed out that as time goes on and facts accumulate he is more and more convinced that the difference between so-called alpha and beta iron is not a difference of allotropic state or condition, such as between gamma iron and the stable varieties in the cold condition. His words are :—

"Je suis de plus en plus convaincu que la différence entre le fer α et le fer β n'est pas une différence d'état allotropique, comme entre le fer γ et les variétés stables à froid. Tous les corps magnétiques, sans aucune exception présentent, à une certaine température, la même chute progressive des propriétés magnétiques. C'est un phénomène caractéristique des corps magnétiques et seulement de ceux là."

Moreover, there are iron alloys now well known and in use which are more magnetic than iron itself. Under the allotropic theory would not this perforce mean still another form of iron, which seems unten-

Sir Robert Hadfield.

able? Apparently this is the only explanation upon which the allotropist can fall back—that is, in view of his previous claims that the differences in the magnetic properties of iron alloys, including those which are non-magnetic, are owing to the particular form or condition of iron existing in them.

As bearing on this question of allotropy, in which magnetic condition really plays a considerable part—that is, according to the theories of the allotropist—Professor Knowlton has pointed out in his paper on "The Present State of our Knowledge of Magnetic Materials" that these vary in what he terms "atomic susceptibility, which bears no relation to the ordinary or mass susceptibility," whilst "ferro-magnetism is undoubtedly neither atomic nor molecular, but crystalline." Here is the statement in full with which he concludes his paper: "Dia-magnetism in all cases, except possibly bismuth and the Cu and Sn alloys of Clifford, is to be regarded as an atomic property, as is also para-magnetism in the narrower sense of the term, while ferro-magnetism is undoubtedly neither atomic nor molecular, but crystalline. Indeed, it is questionable if the word molecule has in the present state of our knowledge any definite physical significance whatever when applied to matter in the solid state. Is there any evidence for the so-called molecular theory which will not apply equally well to prove that magnetism is a crystalline property?" This throws out a new line of thought, which seems to offer a more satisfactory conclusion than those hitherto advanced in this particular field of research.

I am glad Mr. McCance has pointed out M. H. le Chatelier's interesting experiments with regard to the expansion of carbon steels. He discovered that all steels, whatever may be their carbon content, expanded at the same rate up to about 700° C., but above this a contraction set in which varied in amount and took place at different temperatures with changes in the content of carbon. This is very important.

I understand Professor Hopkinson, when replying to the oral discussion on this joint paper by him and myself, mentioned with reference to the critical point 750° C., at which point the magnetism of iron disappeared quite suddenly, he considered this result was suggestive as to the nature of magnetism. His view was that it seemed probable that temperature had an effect on the molecular constitution, and it was a question whether reduced magnetism arose from the total destruction of the magnetism of certain molecules, or whether it arose from a gradual change taking place in all the molecules. The former was more probably the correct explanation. This shows that we cannot generalise upon this question. We must have more evidence before pronouncing positively as to the many peculiarities noticed in the behaviour of iron alloys.

To sum up, we evidently want much more light as to the molecular constitution of the metal iron itself, or, to use Professor Knowlton's term, to study the peculiar grouping of the ultimate particles, or mole-

cules in the chemical sense, of the metal iron, before we can make any further important advance in the direction desired by the electrical engineer. The problem will no doubt be solved, but to do this will also mean investigations probably on quite new lines of thought. As Professor Knowlton points out, the subject is already recognised to be of the greatest importance, seeing that *Science Abstracts* since 1900 contains references to more than 500 papers on the question of magnetic materials and their properties. Yet we are still very much in the dark on many important matters. It is here where the pure scientist can assist, and no doubt he will do this and come to our rescue. Sir Robert Hadfield.

I note with much interest M. Osmond's valuable contribution, and that he says that part of the allotropic theory which attributes the properties of martensite to beta iron is by this research rendered untenable. This is most important. It will be interesting to see how the further suggestions he makes agree with certain investigations which are now proceeding. Until these are completed, and the points relating to them more fully determined, it seems advisable to make no positive reply on several of the statements referred to by M. Osmond. In any case, it is a great pleasure to both the authors of this paper that M. Osmond has seen his way to send a contribution to this discussion on points which are of interesting nature. He makes certain inquiries with regard to the treatment of the specimens. In reply, it may be mentioned that in all cases where specimens have been subjected to heat-treatment, this treatment has not been carried out on the same size piece as tested magnetically, but on a larger piece.

Specimens 13*a*, 13*b*, 14, and XIV*a* were heat-treated in the form of a small fragment of the ingot, weighing about one ounce. Specimen XIV*b* was heat-treated in the form of a ground specimen ¼ in. in diameter by 1 in. long.

Specimens 15*a*, 15*b*, and 35 were small fragments also weighing about one ounce, the piece for the magnetic test being cut out of the heated piece.

Specimens 16*a*, 16*b*, 17*a*, 17*b*, 17*c*, 18*a*, 18*b*, 36*a*, and 36*b* were quenched in water from the crucible in which they were melted, and the magnetic test-piece cut out afterwards.

All other specimens were heat-treated in the form of short rods 1 inch long by 0·22 in. in diameter, the magnetic test-piece being afterwards cut out. To avoid superficial decarburisation, the specimens were heated as quickly as possible for temperatures up to 1,050° C., and those about 1,050° C. were encased in an iron sheath. Although this may not have entirely done away with decarburisation, it is believed the method adopted was sufficiently effective to prevent any loss of carbon taking place from the centre of the mass from which the magnetic test-piece was taken.

Professor B. HOPKINSON (*in reply*): Professor S. P. Thompson asked a number of questions, and also asked for further information on certain points. I can answer him with regard to several of Professor Hopkinson.

Professor Hopkinson.

them at once, but others may require further consideration. He inquired to what value H was carried for the various pieces in Appendix IV. I think in every case, with quite a few exceptions, those pieces were tested up to a maximum of 25,000 C.G.S. units. That was the highest we could reach. There were a few which were taken up to about 14,000 or 15,000, and they were done by that differential method which I have described. At all events, every piece was tested up to saturation. Saturation was shown either by comparison of I at 25,000 with the value at 2,000, or else it was shown by the straightness of the magnetising curve, such as you see on the wall. He also asked for the ultimate permeability, and suggested that I might broaden the table. There was a good deal of information we should have liked to put into that table, but I am afraid if we had done so it would have become of inordinate breadth. The value of I is given in the table as a percentage of the value for pure iron, and the absolute value is at once obtained by multiplying by 1,680. The permeability is then readily worked out; in the case of pure iron the permeability in a field of 25,000 is 1·85. Professor Thompson made some remarks of considerable interest about the permeability of the non-magnetic manganese steel. He said that he had always had difficulty in understanding how this body could have a constant permeability of 1·4. My father, Dr. John Hopkinson, found a constant permeability of about that amount, but he worked with weak fields. I think there can be little doubt now that there is no steel which has a constant permeability of 1·3 or 1·4 in fields exceeding 1,000 C.G.S. None of the manganese steels examined by us have that property. The reason of the apparent discrepancy with my father's result is, I think, not difficult to understand. In low fields, such as he experimented with, viz., up to about 200 units, it might well happen that a steel would show a constant permeability of 1·3 or 1·4. That would occur if the material contained only a small amount of magnetic stuff, and was therefore, magnetically speaking, very soft. Yet that same material could easily have, in consequence of the small quantity of magnetisable material, a very small ultimate magnetic intensity. The actual permeability of the manganese steel 1,010 W.T. that we experimented with in these high fields certainly did not differ from unity by more than 1 per cent.—of that there is no doubt at all—but it is quite possible that if we had been able to test it in a field of 200 units we should have found a permeability materially exceeding unity. Ewing's result obtained with that same steel is more difficult to explain. I have put a possible explanation in a footnote in the paper. Professor Thompson remarked that no end correction was needed for the non-magnetic materials. Of course that would be so, and when I spoke of the end correction of 16 per cent. I meant the correction applied to the measurement of I. In a nearly non-magnetic material 16 per cent. of the magnetism is an unmeasurable quantity from our point of view. As regards the effect of quenching, which was also referred to by Professor Thompson, and the possibility of discriminating between *a*,

β, and γ iron, that is a very thorny question. I think it may be possible in the future to learn something about the modifications of iron by these means, but at present I think it better to say nothing about them. "Magnetic hardness" is a phrase which I believe was used by Barrett, Brown, and Hadfield in the joint paper read before the Institution some years ago. It was the reading of that paper which suggested the phrase to me, and I have used it in much the same sense as Barrett did. I do not attach any definite numerical meaning to it, but I use it to express in a general way the rate at which the magnetism of the material approaches the saturation value. Professor Hopkinson

Mr. Sears asked whether it had been proved that a compound does behave as a mixture. I should put it a little differently—rather that a mixture behaves as a mixture. Take the instance of an iron-carbon alloy. In the case of an annealed iron-carbon alloy we have proved experimentally that the loss of magnetism is a linear function of the amount of carbon. There is good reason to suppose that the stuff is a mixture of iron and iron carbide, and that those two constituents do not influence each other magnetically. On that assumption we have calculated from the results what the magnetism of the iron carbide is. Of course it may be as Mr. Sears suggests, that the presence of the iron affects the magnetism of iron carbide, but I do not think that is so, because we are there dealing undoubtedly with a mixture. The microscopical results prove that, and chemical analysis proves that the constituents of the mixture are iron and iron carbide of the composition Fe_3C. We know, as certainly as we know anything about a mixture of that type, that the magnetism of the whole would be the sum of the magnetism of the constituents, and we have used that fact to find out what is the magnetism of the second constituent, a quantity hitherto unknown. That is really what that experiment amounts to. Mr. Mordey raised one point which I will refer to because it has an important bearing on the methods of investigation described in this paper. He said that pure iron was a most unsatisfactory material because of its want of magnetic permanence. He said it was very unstable, and that he could hardly look at it without its magnetic properties changing. That is true, of course, in the fields employed in the ordinary methods of testing, but it quite ceases to be true when you push the induction to very high values, and that fact illustrates very well, I think, the value of this method of testing as a means of research—not so much for finding out magnetic properties which are likely to be of practical use, but as a method of research into the constitution of materials. The same pure iron which in low fields is completely upset magnetically by, say, a small amount of mechanical disturbance—a little hammering, or something of that kind, which does not distort it in any way—is wholly unaffected, if you only push the induction sufficiently high, even by a very large amount of mechanical disturbance. I have tried, for instance, taking a piece of nearly pure Swedish iron and placing it between the poles of a big magnet, subjecting it to a force of about 5,000, which is adequate to

Professor Hopkinson.

saturate it, and pulling the piece out by means of rods with a screwing arrangement going through the pole-pieces, so as to give it a considerable amount of permanent extension, stretching it, in fact, beyond its elastic limit, and even when subjected to that drastic treatment the saturation value of the magnetism of the iron remains quite unaffected. It is, in fact, a remarkably constant property, and a variation in it implies a real change in the nature of the material, and not a mere rearrangement of parts. We did not make any measurement of specific resistance nor of hysteresis losses. Measurements of that kind were made on a considerable number of these materials by Barrett and Brown and Hadfield.

Mr. Murdoch referred to the unsatisfactory character of the ballistic method of testing. Here again I think there is something to be said for that view as applied to low fields, but I do not think it affects the matter very much in very high fields when the material becomes saturated. It does not matter how you approach the ultimate magnetic force so long only as it is high enough. The same intensity of magnetism is always reached. Apparently there is no time effect. Of course all these things are to be expected according to Ewing's theory. Mr. Stoney asked whether we could not get a non-magnetic steel with 30 to 40 tons tensile strength and good elongation. The interest of that remark to me is that it suggests the possibility of using this method of research, not so much for testing properties of immediate use in electrical engineering, but as a means of investigating the constitution of steels and so producing new steels having different magnetic properties and also different mechanical properties from the older varieties. Mr. Morris asked a question as to the manner in which the saturation value of I varies with the temperature. That is a matter which has recently been investigated by an advanced student at Cambridge, Mr. E. F. Clark, who has fully confirmed the conclusions to which M. Curie was led some years ago by experiments in rather lower fields. The effect of raising the temperature is to reduce the saturation value of the intensity of magnetism. I am speaking now of pure or nearly pure iron. It reduces the saturation intensity from the very beginning. An increase of temperature even of 400° C. reduces the maximum intensity of magnetisation, and the reduction goes on at an increasing rate until the critical point of about 750° C. is reached, when the magnetism disappears altogether. It disappears rather suddenly at the finish, but it diminishes steadily from the very beginning. I think some reduction is perceptible even at 200° C. At all temperatures the material shows saturation just as distinctly as it does at low temperatures. Those results are rather suggestive as to the nature of magnetism. The fact of a reduction of magnetism produced by heating, say, to 400° C., proves to my mind that the temperature has a direct effect upon the individual molecules or magnets. The interesting question is, How does it affect them? Does it destroy the magnetism of some by changing their constitution completely and leave the magnetism of the others unchanged, so that what we have got at a higher temperature is

fewer magnetic molecules, but those few of the same kind as before? Or does it change all the molecules in a gradual way? I confess I think the first hypothesis seems a good deal the more probable. It seems to me that probably the effect of temperature, which we conceive as a motion of the molecules as a whole rather than as an internal movement, is to change the nature of some molecules and leave the others totally unchanged. That, however, is largely a matter of speculation; the facts are as I have stated. I was very glad that Mr. Main, Sir Robert Hadfield's assistant, has been able to be present and to speak in the discussion. I do not quite agree with him that very little of the work was done at Sheffield. Of course, in the particular research described in this paper, no doubt that is so; the greater part of the work was done at Cambridge. But the basis of the whole thing is undoubtedly the remarkable series of steels which was made some years ago by Sir Robert Hadfield and which has been so very fruitful in producing research of various kinds. While on this subject, and before I sit down, I should like to say that it is quite impossible to carry through any research of this character without a large amount of assistance. My own actual personal work in this matter has been really comparatively small. I have had a number of most efficient assistants, many of them working for the love of it. They have been students at the University of Cambridge, and between them they have done pretty well the whole of the experiments and a great deal of the calculation. I should like particularly to mention the name of one of my assistants, Mr. Quinney, who has really carried through a good half of it.

Professor Hopkinson.

Communicated: Professor Arnold suggested that the falling off in the magnetic capacity of quenched steels is possibly due to cracks. Professor MacWilliam made a similar suggestion with regard to the results obtained with 1391 B. I do not think, however, that such cracks can affect the matter in the intense fields used in this research, though in the moderate fields employed in ordinary testing their effect would be considerable. It is indeed one of the chief advantages of magnetic testing in a very strong field, regarded as a means of investigating the constitution of steel, that the ultimate magnetism of steel (which is revealed in such tests) is independent of such accidental factors as the presence of cracks, the size of crystalline grains, etc.

Mr. Hoyle asks about the relation between the "end effect" and the length of the specimen. In the tests between flat pole-pieces in fields of about 5,000 C.G.S. the end effect is equivalent to a constant addition to the length of the specimen amounting to about 0·12 mm. I think there is no doubt that the correction can be applied in this form on specimens of about a quarter of an inch long, such as are described in the paper, but it would not be advisable to apply it to shorter specimens since the ends would interfere with each other. I do not think that the size of the pole-faces makes much difference so long as it is adequate to give a uniform field along the whole length of the specimen. The junction between the specimens and the pole-faces plays a large part in determining the end effect in moderate fields, but is practically

Professor Hopkinson.

without influence when H exceeds about 5,000 units; this is shown in Fig. 4 of the paper.

The expression in Appendix III. to which Mr. Hoyle refers means that the difference has to be taken between the values of the expression in the square bracket, when for z and r are substituted, first, z_2 and r_2 respectively, and second, z_1 and r_1 respectively.

The President.

The PRESIDENT: I hope you will give a very hearty vote of thanks to the authors for their most interesting paper.

The motion was then put and carried with acclamation.

The PRESIDENT: We now have to hold a meeting of the Members, Associate Members, and Associates, and I will ask any visitors or students to withdraw from the meeting.

A Special General Meeting of Members, Associate Members, and Associates, duly convened and held in the Theatre of the Institution, Victoria Embankment, W.C., on Thursday evening, December 8, 1910—Mr. S. Z. DE FERRANTI, President, in the chair.

The President read the notice convening the meeting.

The PRESIDENT: I now formally move: "That the action of the Council in borrowing (under the powers given to them by the Members, Associate Members, and Associates assembled in Special General Meeting on June 30, 1908) the sum of £11,500 from the Economic Life Assurance Society on the security of the freehold and leasehold property of the Institution, being Nos. 15, 16, 17, and 18, Tothill Street, Westminster, on the terms of the Indenture of Mortgage dated 15th July, 1910, a copy of which is now produced at the meeting, be and is hereby authorised and confirmed."

Mr. ALEXANDER SIEMENS: I have much pleasure in seconding the resolution.

The PRESIDENT: The resolution is now open to discussion.

No remarks having been offered, the Resolution was then put to the meeting, and declared by the President to be carried.

Proceedings of the Five Hundred and Thirteenth Ordinary General Meeting of the Institution of Electrical Engineers, held on Thursday, December 15, 1910—Mr. S. Z. de Ferranti, President, in the chair.

The minutes of the Ordinary General Meeting held on December 8, 1910, were taken as read, and confirmed.

The list of candidates for election into the Institution was taken as read, and it was ordered that it should be suspended in the hall.

Messrs. J. W. Fraser and T. L. Horn were appointed scrutineers of the ballot for the election of new members, and, at the end of the meeting, the following were declared to have been duly elected :—

ELECTIONS.

As Associate Members.

Harry Heaton Brierley.
Sydney Edmund Day.
Roseman Edward H. Lovelace.
Henry William Malcolm.
Harry Francis Nottage.

As Students.

Leslie Frank Burgess.
Charles Stuart Buyers.
Brian Charles Clayton.
Alfred William B. Head.
Archibald Davidson Peacock.
Reginald William Riley.

The following paper, "Submarine Cables for Long-distance Telephone Circuits," by Major W. A. J. O'Meara, C.M.G., Member, was read and discussed, and the meeting adjourned at 9.30 p.m.

SUBMARINE CABLES FOR LONG-DISTANCE TELEPHONE CIRCUITS.

By Major W. A. J. O'Meara, C.M.G., Member.

(*Paper received November* 4, 1910, *and read before* The Institution *on December* 15, 1910.)

Introduction.

An examination of the *Journal* of the Institution shows not only that it is some years since any paper was read on the subject of submarine cables, but that no account at all of the work done in connection with the development of submarine cables for long-distance telephones has yet been presented to our members.

The reason for this is perhaps not far to seek. Up to a very recent date, little departure had been proposed in the standard specification for the submarine type of telegraph cable in order to adapt it to meet the requirements of a telephone circuit, although it had long been recognised that really serious limitations were imposed on the extension in the range of long-distance telephone transmission when the obstacle met with consisted of a wide expanse of open water subject to the disturbing influences of tide, weather, and traffic.

It is generally recognised that it is very desirable that the *Journal* of this Institution shall contain such a complete record of the development in every sphere of electrical engineering as will afford an accurate history of the progress which has taken place from time to time in the various electrical industries. I propose therefore to place before the members of this Institution a short account of a small portion of the work of the officers of the Engineering Department of the British Post Office, the character of which will perhaps be readily admitted to be not only of great importance to our own country, in relation to trade, commerce, and social amenities, but also of considerable influence upon our international relations. Further, I hope that this information which has been collected will help to fill up pages in our *Journal*, which may, to some extent, be considered blank at the present time. My task to-night is much facilitated by the fact that it is not necessary to go deeply into the theoretical aspects of the subject of the transmission of telephonic speech, owing to the admirable manner in which this subject has already been presented to the Institution in an interesting and valuable paper by Messrs. Cohen and Shepherd.*

* *Journal of the Institution of Electrical Engineers*, vol. 39, p. 503, 1907

Early Submarine Telephone Cables.

The first submarine cable of any length specially designed and provided for telephonic purposes by the British Post Office was that between St. Margaret's Bay and Sangatte, laid in 1891; at that time the intention was to limit the use of this cable to the provision of telephonic facilities between London and Paris. Since then, many other cables have been laid (*vide* Appendix I.), and these have all been practically of the same type. The weight of copper and gutta percha in the cores was so proportioned as to make them specially suitable for use in connection with considerable lengths of land wires. The Port Mora-Donaghadee cable, for example, connecting the English and Irish telephone systems forms a link between 400 or 500 miles of land line on each side. The data available in 1890, when the first Anglo-French cable (referred to above) was designed by Mr. H. R. Kempe, now Electrician to the British Post Office, were naturally somewhat incomplete, but the results obtained with the first telephonic circuit between London and Paris have proved eminently satisfactory from the date of its first use. This has been testified to by the demand of the public, not only for additional facilities between England and France, but also for the establishment of telephonic communication between England and Belgium. In the latter case facilities were provided in the year 1902.

I was serving as a subaltern in the 2nd Division Telegraph Battalion Royal Engineers (now "K" Company R.E.) in 1890, and became in this way associated with the work of establishing the first international telephone circuit affecting this country, for I was charged with the duty of making all the necessary arrangements for the selection of a suitable route for the lines from London to the coast, the preparation of the estimates and the superintendence of the construction of the works necessary on this side of the water. I can still recall the anxiety that existed twenty years ago in relation to the elements of the problems concerning which so little practical knowledge existed, and which it was felt might have such an important influence on the success or failure of the scheme in hand. Very strict instructions were issued to ensure, not only that the wires of the aerial section should be fastened to the insulators in such manner that the centres of the four wires of a twisted group would form the corners of a true square at these points, but also that the poles themselves should, as far as possible, be the same distance apart. Great care was at the same time taken to reduce the use of gutta percha covered wires to a minimum, and for this purpose the usual practice of leading wires into the more important post offices on the route for facilitating the localisation of faults was abandoned. The first precaution is still observed, but the same attention is not demanded to-day in respect of the uniform spacing of the poles, and the introduction of paper-insulated cables has permitted a return to the normal practice of looping the conductors into the important post offices for testing purposes.

The laying of the first cable (constructed by Messrs. Siemens Bros. & Co.) was carried out by H.M.T.S. *Monarch*, under the command of the late Mr. D. Lumsden. This operation was commenced on the French coast on March 9, 1891, on which date the French shore end was landed, the weather being favourable and fine. The late Mr. E. Graves, then Engineer-in-Chief, Mr. (now Sir) William Preece, then Electrician, and other officials from the General Post Office, had proceeded to St. Margaret's Bay to await the arrival of the *Monarch*. Shortly after the cable ship had come within sight of the English coast, it was overtaken by a sudden and violent snowstorm ; the sea became very rough, and Mr. Lumsden found it necessary to cut the cable and run for shelter. For a time doubt existed as to the safety of the *Monarch*, which had completely disappeared from our view. It was not until the 12th of March that operations were again commenced and the laying of the cable completed. Within a few days after the end of the cable had been landed at St. Margaret's Bay, good commercial speech was proved possible between London and Paris.

Descriptions of the first British International telephone cable have already been published.* The essential particulars have been extracted, and are given in Appendix II.

Experimental Provision of Air-space Submarine Cable.

From time to time, the several Administrations charged with providing international telephonic services have been called upon to extend the range of communication. The problems connected with the transmission of speech have in consequence been kept constantly before their engineers, and have received close study. A slight departure from the original type of cable employed was considered in 1897, when the question of providing telephonic facilities to the Isle of Wight was first raised. It was well known some fifty years ago that the high electrostatic capacity of gutta percha covered conductors greatly affected the transmission of electric impulses, but it was not until 1887 that a satisfactory theory of telephonic transmission was formulated. In that year, Oliver Heaviside † gave the essential parts of the theory of telephonic transmission, pointing out the importance and beneficial effects of self-induction and stating the relation which must exist between the constants of a circuit in order that electrical waves of all frequencies may be transmitted without distortion. His investigations show great power of mathematical analysis and a wonderful insight into complex electrical phenomena. To him most certainly belongs the credit of being the earliest investigator in the field of telephony to predict the measures necessary for progress in the art of speech transmission. Unfortunately, however, it was many years before any attempt was made by engineers to apply the mathematical deductions which Oliver Heaviside had placed within

* *Electrical Review*, vol. 27, p. 309, 1890, and vol. 29, p. 247, 1891.
† *Electrician*, vol. 19, p. 79, 1887 ; Electrical papers, vol. 2, p. 119.

their reach, to the solution of practical problems in connection with long-distance telephony.

The difficulties which manufacturers may experience in realising the specifications of the practical engineer have always to be considered whenever a wide departure from existing types of cable is proposed. So far back as 1891 Silvanus P. Thompson obtained a patent for "Improvements in means for use in or in connection with the conveyance of varying electric impulses, applicable to electric signalling for telegraphic, telephonic, or other purposes" (Patent Specification No. 22304, of 1891). The improvements suggested were the employment of distributed inductances, leaks, etc., and this patent specification may be considered to have afforded independent testimony to Heaviside's views. Engineers, however, were not convinced as to the practicability of effecting improvements in telephonic transmission by this means, and therefore a solution to the problem was sought by devising a method for materially reducing the electrostatic capacity of submarine cables. A proposal which contemplated a solution of the problem in this manner was placed before the British Post Office and was readily accepted. The air-space type of cable designed by Messrs. Willoughby S. Smith and W. P. Granville (Patent Specification No. 8573, of 1895) was, in 1897, brought to the notice of Sir William Preece, then Engineer-in-Chief to the British Post Office. The extension of the telephone trunk service to the Isle of Wight had just been sanctioned, and it was felt that a suitable opportunity existed for the employment of the air-space type of cable for the projected service. Further, it was hoped that data of a practical kind likely to prove useful in connection with future developments would be obtained by a trial of this type of cable, and in consequence, communication between the mainland and the Isle of Wight was provided by an air-space cable laid between Stone Point and Gurnard Bay, a distance of about two knots, on June 30, 1897.

The electrical tests carried out when the cable was laid proved it to be in every way satisfactory. Speech tests were also made and disclosed no feature in the design likely to cause difficulty in practice. It was discovered later, however, that this apparent freedom from defects was due to the fact that the cable under test was of too short a length for a complete investigation of its telephonic efficiency to be made. The practicability of manufacturing long lengths of this type of cable, with conductors symmetrically arranged throughout their whole length, had not in fact been proved; but, at the time, the results of the tests were considered sufficiently encouraging to justify the adoption of this type of cable in connection with problems of greater magnitude, so that when an increase in the number of telephone circuits between England and Ireland was suggested in 1898, this type of cable was adopted for the purpose.

The Gutta Percha Company has most courteously supplied a short description of the method used in the manufacture of the 4-core gutta percha insulated air-space cable laid between Nevin, Wales, and

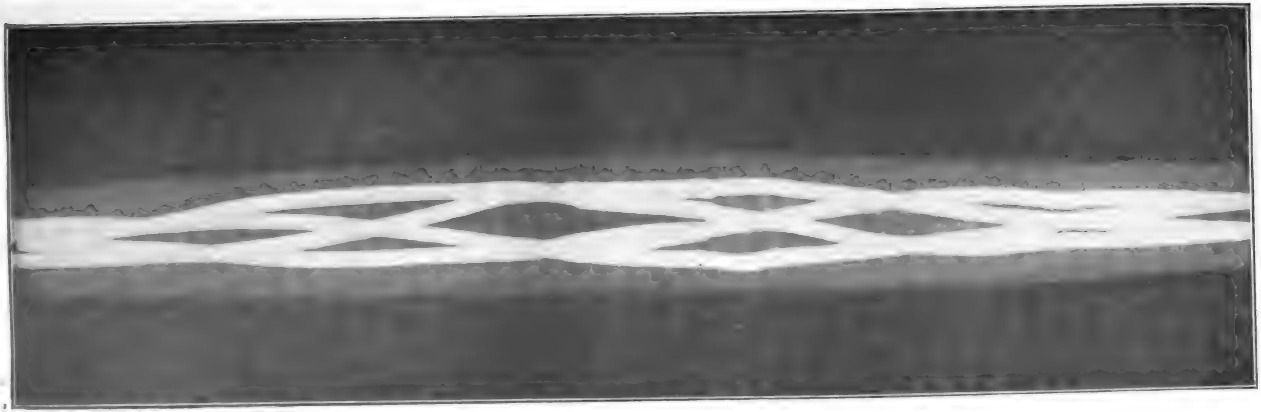


FIG. 1.—Radiogram of Joint in Air-space Gutta Percha Cable between Wales and Ireland.

Newcastle, Ireland (Appendix III.). As a matter of interest, it may be mentioned that this Company utilised the Röntgen rays for the examination of the joints made in the cable, and permission has kindly been given for the publication of the radiogram (Fig. 1), which clearly brings out the arrangement of the conductors and the method employed in connecting them together at junctions of the several sections of the cable. When this Anglo-Irish cable was tested under practical conditions, a very serious defect was discovered, namely, that when two telephonic circuits were formed on the four wires, it was not possible to carry on conversation simultaneously without overhearing; in fact, serious inductive disturbances existed between one pair of conductors in the cable and the other pair.

Great disappointment was experienced when this fact came to light, and to clear up the situation a series of experiments was arranged in May and August, 1900, by Mr. (now Sir) John Gavey on the three cables (two telegraph and one telephone) which at that time connected Nevin, in Wales, and Newcastle, co. Wicklow (Appendix IV.). These experiments were intended to determine—

(*a*) The relative volumes of sound in each cable, the terminal conditions being maintained the same in the three cases.

(*b*) Whether overhearing existed between diagonal pairs of wires in any of the cables, and, if so, to what extent.

(*c*) Whether speech was practicable through two cables of standard telegraph type (107 lbs. copper, 150 lbs. gutta percha) when joined in series—*i.e.*, over 120 knots of this type of cable.

(*d*) Whether the four wires of the telegraph cables joined in multiple would improve speech as compared with that of a metallic circuit in the same cables; that is, to ascertain what effect a decrease of resistance and a corresponding increase of capacity would have on telephonic transmission, and—

(*e*) Whether the superimposing of a telegraph circuit on a telephone loop materially lessens the efficiency of the telephone circuit.

The results were as follows:—

(*a*) *No.* 1 *Telegraph Cable.*—Volume of sound sufficient for commercial purposes, but no margin for extension; articulation well defined.

No. 2 *Telegraph Cable.*—Volume slightly in excess of No. 1; articulation very well defined.

Telephone Cable.—Volume excellent on each pair of diagonal wires; conversation could be carried on with receiver some inches away from ear.

(*b*) *No.* 1 *Telegraph Cable.*—There was a very faint trace of overhearing between diagonal pairs, probably due to the "twist" having

been removed at the point where the cable was led into a hut at one of the landing-places.

No. 2 Telegraph Cable.—There was no overhearing between diagonal pairs of wires.

Telephone Cable.—The overhearing between diagonal pairs of wires was so loud and distinct as to result in the conversation on one pair of wires being easily heard on the other pair by induction.

(*c*) Speaking was just practicable between experts.

(*d*) Speaking was less practicable than in the preceding experiment.

(*e*) The volume was reduced by about one-fourth, and the articulation somewhat blurred.

The following conclusions were definitely drawn from the foregoing experiments :—

1. Commercial telephonic communication between terminal points connected by a 60-knot length of the ordinary submarine telegraph cable of the standard type is possible, but there is no margin available under such conditions, for extending the range of communication beyond that distance.

2. The air-space type of cable of a similar length—60 knots—does afford a sufficient margin for extending the range of telephonic communication very appreciably if combined with suitable aerial conductors, but the existence of overhearing between the two pairs of conductors, and the disturbances introduced by utilising one pair of wires for telephonic purposes and the other two wires simultaneously for high-speed telegraphic purposes, precludes the employment of this type of cable for telephonic purposes wholly, or for joint telephonic and telegraphic purposes, unless the telegraph circuits are impeded and worked at a low speed.

Within the last two or three years, a further series of experiments have been carried out on the Anglo-Irish air-space cable with a view to eliminating if possible the disturbances referred to. The experiments were designed with great care and were carried out for a prolonged period, but the results showed that the proposal, which had been revived, to utilise this particular cable for the purpose for which it was originally intended, would have to be again abandoned, at least for the present. There appears to be little doubt that the cause of the failure of this type of cable is due wholly to the difficulty in manufacturing it in such a manner as to ensure that the conductors shall retain the positions they are intended to occupy, *i.e.*, so that their centres shall form at every cross-section a true square.

Proposals involving the Provision of Additional Telephone Facilities between England and France.

When the question of laying an Anglo-Belgian cable in order to establish direct telephonic communication between London and Brussels came up for consideration, it was decided, in view of the failure of the air-space cable, to use the same type as the original

Anglo-French cable. The length of cable required was about 50 knots, and as it had been proved by experiments on circuits formed by looping the conductors of the cross-channel telephone cables that good speaking was possible through 80 knots of this type, it was therefore quite safe to lay 50 knots, and it was probably a wise decision to use a proved rather than an unproved cable.

In 1908 the French and British Administrations found that the public demand for telephone facilities between the two countries had increased, and as a result of the negotiations between the Postmaster-General and the French Government it was decided to provide four additional circuits (*i.e.*, two new cables) between England and France, each country providing and laying one.

In considering the best means for providing the additional circuits it was recognised that it was not a matter in which the problem consisted merely of increasing the existing number of channels of communication, but one which afforded an opportunity, whilst providing the additional facilities required, to extend the range of intercommunication so as to embrace centres not hitherto included in the international zones owing to the great distances separating them. The consideration of the problem from this point of view naturally involved the utilisation of all the information on the subject of telephone transmission which had been accumulated in the Engineering Department during the past few years, in order that the design of the cable should admit of the realisation of the greatest practical increase in its efficiency at a moderate cost.

Three methods of increasing the range of telephonic transmission, so far as submarine cables are concerned, have been prominently before the Engineer-in-Chief's staff, viz :—

(*a*) By the use of heavier copper conductors, and by an increase, at the same time, of the separation between them.

(*b*) By the provision of one or more closely arranged layers of suitable iron wire over the whole length of the copper conductors in the cable—the so-called "continuous" loading system.

(*c*) By the introduction at regular intervals of suitably arranged inductance or loading coils—the so-called "non-continuous" or "coil" loading system.

Two varieties of cable in which it was proposed to obtain increased efficiency in transmission by the employment of a larger quantity of copper per unit of length have been submitted to the Engineering Department, and, needless to say, these have been very carefully considered. In both of these designs, provision has been made for the introduction of layers of paper between the copper and the gutta percha. Some particulars regarding these cables will be found in Appendix V., and it will be seen that each of them contains only a single circuit.

According to our present experience, paper appears to be a somewhat unsuitable material to employ in the manner proposed on account

of its hygroscopic qualities which cause it to absorb moisture from the gutta percha, quite apart from the question of the probable high cost of maintenance that a cable in which paper is used may involve. However, an effort is being made to discover some effective means of overcoming the practical difficulties which have been encountered, owing to the moisture exuding from the gutta percha.

A diagram of sections of various types of telephone cables that have been adopted or proposed is given in Appendix VI.

The problem is naturally one in which commercial considerations are paramount. Even a Government Department cannot really afford to provide public utility services at a very great loss, and it has been the desire of the British Post Office so to lay out its plant, especially in connection with telephonic development, that the annual revenue shall at least be equal to the annual expenditure. The natural desire of the telephone engineer is to have ready at all times schemes for extending the range of communication, in order to anticipate the demands of the public in this direction.

The question of providing cables of higher efficiency comes under consideration only as the distances of the points between which they are required become relatively great; in such cases the magnitude of the capital cost involved in providing the cables rises in a nearly geometrical ratio if the problem is solved by the simple expedient of increasing the weight of the copper conductors, and for this reason proposals for heavier copper conductor types of cable have in recent times been in abeyance.

The two practical methods—that of "continuous" loading and of "non-continuous" loading—have been the only ones considered, therefore, in connection with the proposal to increase the number of cross-channel communications. Needless to say, the advantages and disadvantages of these two types of cable have been very thoroughly studied. All available literature bearing on the subject has been scrutinised, and such information relating to those types of cable which have already been laid by Foreign Administrations have been obtained. For convenience a schedule is given in Appendix VII. of some foreign loaded submarine telephone cables which have been provided in the past,* together with a short description of what is involved in connection with the design of the "continuously" loaded type of cable. The latter type of cable certainly appears to offer an advantage, as being mechanically simpler than the "coil" loaded cable, but our investigations have shown that the increase in efficiency which it was desired to obtain could only be realised at an incommensurate cost. Moreover, it has been found that it is not possible to predict with sufficient accuracy, by mathematical calculation, the results likely to be obtained by the "continuous" loading, owing to the difficulty in attaching correct values to the electrical constants involved. In theory, the designing of a cable of this type

* *Elektrotechnische Zeitschrift*, vol. 29, p. 586, 1908; and also *Journal Télégraphique*, vol. 29, p. 187, 1905.

seems to require merely the solution of the apparently simple problem of ascertaining the increase of inductance which can be obtained by providing layers of iron wire or tape of known permeability over copper conductors of known diameter, assuming that the nature of the

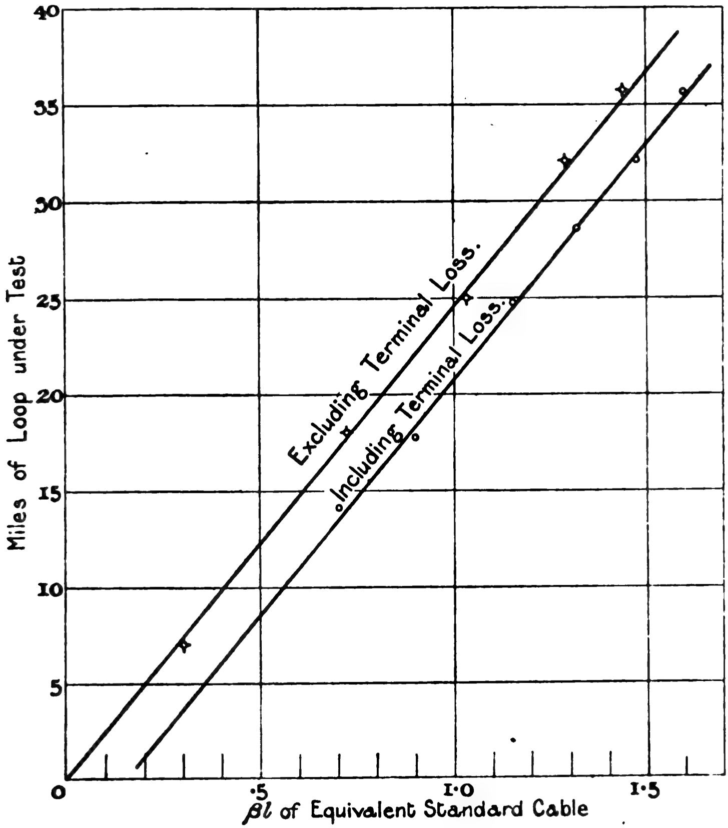


FIG. 2.—Efficiency Tests of "Continuously" Loaded Cable.

Length, 1·78 miles. Type, 4 quads + 12 pairs.
Copper, 2 mm.². Iron, 1 layer 0·37 mm. wire.
Loop resistance per mile, 27·64 ohms.
Wire-to-wire capacity per mile, 0·08 microfarad.
Inductance per mile, unknown.

dielectric to be employed has been determined and that the overall diameter of the finished cable shall remain a fixed dimension.

An expression for the inductance of a loop, each of whose conductors is wrapped with a continuous layer of iron, is given in Appendix VIII. Although such a method of applying the iron would give the greatest possible inductance, either for a given outer diameter

of the iron covering or for a given weight, yet it cannot be adopted owing to the excessively large increase of effective resistance which will accompany the increase of inductance, for at high frequencies the eddy-current loss in such an iron sheath would be impracticably large. Hence the iron covering must be electrically divided, not continuous. In the cables of Appendix VII. the iron was served in the form of one or more layers of wire; and for a loop so loaded, the inductance and increase of effective resistance due to the eddies in the iron may be calculated from the further formula of Appendix VIII.

Messrs. A. W. Martin and J. G. Hill, of the Post Office Engineering Department, recently carried out a series of comparative speech tests on a number of cables of this type by the kind permission of the late Mr. C. E. Krarup, Engineer-in-Chief to the Danish Telegraph Service. The results obtained on one of these cables are shown graphically in

TABLE A.

Based on actual "continuously" loaded cable.
Overall diameter of copper, 126 mils.

Loading.	Outer Diameter of Gutta Percha. Mils.	$\beta \frac{1}{\text{Knot}}$	
		Observed.	Calculated.
Three layers of 7·88 mils iron wire	355	0·0296	0·0197
Unloaded	355	—	0·0369
Coils of 100 millihenries every 1·075 knots ...	335	—	0·0148

Fig. 2. The observed attenuation constants of another of the Danish cables is given in Table A, and for comparison therewith, the attenuation for the same cable as found by calculation, and the attenuations calculated for ideal cables with the same copper conductor are also shown (1) unloaded, and (2) loaded with inductance coils. The details for these calculations are tabulated in Appendix IX. The data given in Table B relate in a similar manner to a cable actually loaded with inductance coils, the attenuations when unloaded and when "continuously" loaded being calculated from the particulars in Appendix IXA.

A wide difference is seen to exist between the ascertained values for attenuation of "continuously" loaded conductors and those which theory seems to predict. The expressions for inductance and eddy-current loss take cognisance of the air-gaps necessarily present in the wire winding, but the eddies are considered as existing in each

circular cross-section of the wire alone, thus assuming that no current flows from one wire of the winding to its neighbours. This is a possible source of discrepancy, but the errors so introduced are probably small. Perhaps a more important source of error lies in the somewhat indeterminate value of the permeability of the iron after it has been wound on the conductor. Change of permeability due to overstrain during the winding of the iron is known to occur, and this may be large. The disagreement between observed and calculated values of the attenuation of cable loaded in this manner requires, and is receiving, further investigation.

The development of telephonic communication by means of conductors in comparatively long lengths of subterranean cables during the past few years has afforded the Post Office Engineering Department a valuable opportunity for making a close study of telephonic transmission under various conditions. In this way very much useful

TABLE B.

Based on actual "coil" loaded cable.
Overall diameter of copper, 106·2 mils.

Loading.	Outer Diameter of Gutta Percha. Mils.	$\beta \frac{1}{\text{Knot}}$	
		Observed.	Calculated.
Coils of 100 millihenries every knot...	390	0·0166	0·0166
Unloaded	390	—	0·0520
Three layers of 7·88 mils iron wire...	405	—	0·0230

information has been accumulated and considerable practical experience has been gained. Mr. H. R. Kempe has gone very carefully into the method of calculating the attenuation of telephone circuits and the cost aspect in regard to the design of gutta percha cable. The results are valuable, and some of them will be found in Appendix X.

Our investigations clearly indicated that it was possible to obtain more appreciable improvements in long-distance telephone cables by employing loading coils than by resorting to the "continuous" loading of the conductors. Therefore when the matter of the provision of additional submarine cables between this country and France was referred to the Engineering Department, inquiries were at once made to ascertain whether it would be practicable to provide, lay, and maintain in a satisfactory manner, a submarine cable of the "coil" loaded type. It was known that a lead-covered cable provided with loading coils had been laid across Lake Constance from Friedrichshafen to Romanshorn; the several features of the problem involved in this case and the method

adopted in actually laying the cable have been fully described.* The conditions under which this cable was laid, however, were entirely different from those requiring the consideration of the Post Office Engineering Department, and it will be recognised that, in view of the difficulties which would arise in the event of the lead sheathing being punctured, it would have been a costly and hazardous experiment to provide and lay a lead-covered cable across the English Channel.

Whilst our investigations were in progress an article appeared † which was somewhat disturbing. As will be seen from the extract given below ‡ doubt was thrown on the possibility of improving transmission in gutta percha covered cables by means of the so-called Pupin coils, on account of the low effective insulation of gutta percha to currents of high frequency. In order to settle the point definitely, it was decided to carry out some experiments. The Department had a large stock of No. 7 gutta percha covered wire (weight of copper, 40 lbs. per mile ; of gutta percha, 50 lbs. per mile ; resistance, 44 ohms per loop mile ; electrostatic capacity wire to wire, 0·13 microfarad per mile), and also a number of inductance coils (inductance, 83 millihenries ; resistance, 13·4 ohms at 750 periods per second), which had been used originally for carrying out some experiments in connection with the improvement of transmission of speech in subterranean cables between Liverpool and Manchester. Calculations were made to ascertain the best disposition of the coils in this particular type of cable—although neither the coils nor the cable were really of the most suitable type—and it was found that in order to provide 55 millihenries per mile they should be inserted at intervals of 1½ miles. A large number of speech tests were made on loaded circuits formed by means of the No. 7 gutta percha wire, by myself, Messrs. H. Hartnell, A. W. Martin, and other members of my staff. It was gratifying to find that the actual improvement in transmission was in complete agreement with the estimates based on the calculations that had been made. (By calculation the attenuation was 0·0436 per mile, and the observed result was 0·0419 per mile.) We found that commercial speech was certainly practicable on 105 miles of this particular type of "coil" loaded gutta percha wire, and our doubts as to the feasibility of the "non-uniform" loading for submarine cables of moderate length were set at rest. The question of providing a "non-uniform" loaded type of cable was therefore proceeded with.

In order to be absolutely on the safe side, however, when preparing the specifications for this new Anglo-French cable, it was decided that the general design of the new telephone cable in respect of the copper and the dielectric should be exactly similar to the type already in use, which it was known would provide telephonic transmission of a certain quality, and that the improvement desired could be obtained by the con-

* *Electrician*, vol. 59, p. 217, 1907.

† *Elektrotechnische Zeitschrift*, vol. 29, 1908, p. 588.

‡ "Es ist danach fraglich, ob man überhaupt Leitungen mit sehr geringer Dämpfung als Guttaperchakabel mit Pupinspulen bauen kann, wenn nicht die dielektrischen Eigenschaften der Guttapercha erheblich verbessert werden."

tractors either by means of "continuous" loading or "coil" loading, the Department simply stipulating in the specification that the attenuation constant should not exceed a certain definite value. The main reason for this was that if it had been discovered after the cable had been laid that coils introduced effects not foreseen, the coils could easily have been cut out at a small cost and the Department would still have had a cable as good as the existing one. (A copy of the specification is given in Appendix XI.) It is known that under certain conditions of design in the relation of the weight of gutta percha to that of copper per knot, an effect is created referred to colloquially as "drumminess." "Drumminess" is a property which causes speech to be muffled, and therefore renders it less distinct. In an unloaded circuit "drumminess" is generally unmistakable, when the ratio $\frac{K^*}{R}$ per mile is equal to 0·003. The greater this ratio the more marked is the "drumminess."

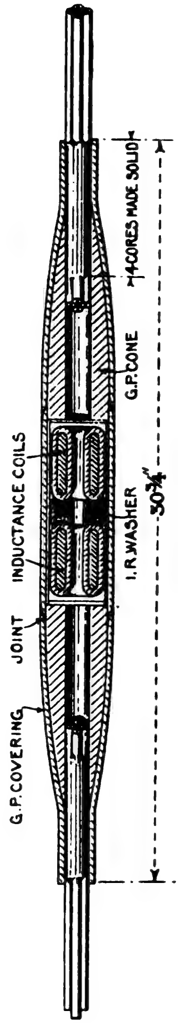
Selected firms were asked to tender for the additional cable to be provided by the British Administration. No tenders were received for the "continuous" type of loading, but three tenders were received for the "coil" type of loading. In each case the method of providing the increased inductance was different. In one case the mechanical aspect of the question had been very carefully gone into, and the device proposed for increasing the inductance was certainly ingenious, but this type of cable did not promise to be quite so efficient electrically as that which was finally selected; the question of cost was also a ruling factor in the situation.

The features of the device for loading in the accepted tender are as follows:—

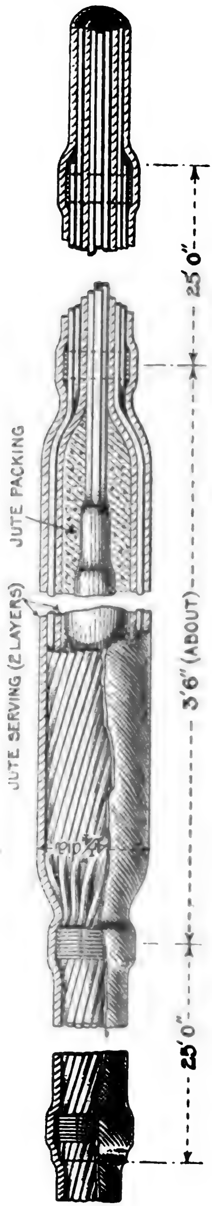
The two double coils required for the four conductors of the cable, each coil being of slightly less than 6 ohms resistance and having an inductance of 0·10 henry at 750 periods per second, are inserted at intervals of 1 knot (1·153 miles), but the two coils nearest the ends of the cable are inserted at a distance of only half a knot from the terminal apparatus, as experiments have shown that in this arrangement reflection losses are considerably reduced. Each double coil consists of two windings on the same iron core, and one winding is connected in series with each conductor. By this means the gradual change in permeability in the iron core due to ageing will not affect the balance in the two limbs of the telephone circuit. Each coil is protected with a sheet of metal foil in order to exclude all possibility of the silk covering of the wires of the coils absorbing moisture from the cylindrical envelope of gutta percha in which they are contained. The cores of the cable are connected to the envelope at its two ends by tapered solid gutta percha joints. The diameter at the centre of the envelope is 3 in., and at the cores where the joints terminate 1 in. An annular rubber distance-piece is inserted between the two coils of a set to give greater flexibility. The total length of the joint is 30·75 in. As the diameter of the cable at the points where

* K = microfarads, and R = ohms.

Fig. 3.—Section of Cable containing Loading Coils, complete with Sheathing Wires.



Arrangement of Coils in Cable
(Scale about one-sixth)



Method of Sheathing over Coils
(Scale about one-sixth)

Fig. 4.—Anglo-French Cable, 1910.

the coils are inserted is increased, a larger number of sheathing wires are required at those points than over the conductors alone. This difficulty is ingeniously overcome by starting a second layer of sheathing wires over the cores, about 27 ft. from the centre of the coil envelope and gradually working them into a single layer with those over the bulge. Finally they are terminated as a second layer again over the cores at a distance of about 27 ft. from the centre of the coil envelope. The method adopted in inserting the coils (Patent Specification No. 5,547 March, 1907) will perhaps be understood from the diagrams (Fig. 4).

It will be recognised that the mechanical problem in connection with this type of cable was more difficult to solve than the electrical problem, as it was necessary that the part of the cable containing the coils should be so designed that it could be paid over the sheaves of the cable-ship without any risk of damage to the coils themselves. However, I am glad to say that the manufacturers succeeded in solving this problem in a most satisfactory manner.

The cable was under the constant supervision of the Post Office Engineering Department during the period of its manufacture, and electrical tests were carried out from time to time. On January 18, 1910, after the completion of the cable, measurements to determine its attenuation constant were made at the works of Messrs. Siemens Bros. & Co. at Woolwich. The conductors of the cable were joined up so as to provide a metallic circuit of 41·704 knots, and in order to get rid of terminal effects artificial cable was joined to the ends of the loaded cable thus:—

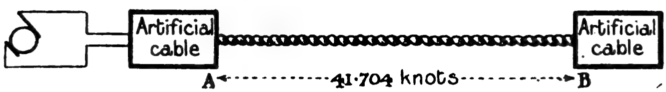


FIG. 5.

Current was supplied to this circuit by a generator giving 1·585 volts at a frequency of 750 alternations per second. Readings were taken on a thermo-galvanometer placed successively at A and B, and the attenuation constant was calculated by the formula $C_B = C_A . e^{-\beta d}$.

With 10 miles of "standard" cable* (attenuation constant 0·1187 per knot) at each end of the circuit the current values at A were found to be 0·327 milliampere, and at B 0·172 milliampere, β therefore being 0·0154.

With 15 miles of "standard" cable at each end of the circuit the current values at A were found to be 0·212 milliampere; at B, 0·110 milliampere, from which we similarly obtain $\beta = 0·0158$.

The volume of the speech transmitted over the loaded cable was also compared with that over an artificial "standard" cable, the elec-

* Sir John Gavey, Inaugural Address, *Journal of the Institution of Electrical Engineers*, vol. 36, p. 26, 1905.

trical constants of which are known. The result of these tests indicated that the attenuation constant of the loaded cable was 0·0147.

If the electrical constants of the Anglo-French loaded cable are substituted in the formula—

$$\beta = \frac{R + \frac{S}{K} L}{2} \sqrt{\frac{K}{L}}$$

it will be seen that the attenuation constant obtained by the sent-and-received current test requires that the value to be assigned to $\frac{S}{K}$ in the above formula must be approximately 99, whereas the value of the attenuation constant indicated by a comparison with the artificial "standard" cable requires the value of $\frac{S}{K}$ to be 80. There is no doubt that leakage plays a very important part in the transmission of telephonic speech. Recently whilst in America, I found that one of the principal difficulties which had been encountered in that country in connection with the loading of long-distance aerial telephone circuits consisting of the larger gauges of wire was chiefly due to leakage. However, the difficulty has been largely overcome by the substitution of more efficient insulators for the glass ones which have hitherto been in general use in the United States.

We have long been aware of the great importance the ratio $\frac{S}{K}$ plays in the design of long-distance telephone circuits. In the case of gutta percha cables there is certainly no noticeable leakage arising from faulty insulation as in the case of aerial wires; still the dielectric currents in such cases are appreciable, and practically represent an effective leakage. Dr. Breisig has informed me that he has carried out various tests on dielectrics and has confirmed the existence of such losses. For viscous dielectrics he finds that the value of $\frac{S}{\omega K}$ (where S is the effective leakage, K capacity in farads, and ω is equal to $2 \pi n$) is independent of the value of K; in the case where $\omega = 5{,}000$ the value is found to be 0·018.

In dealing with the maintenance of "coil" loaded cables after they have been laid, the degree of importance to be attached to the uniform spacing of the coils has to be considered. In repairing cables, intermediate lengths have to be inserted at times, but fortunately if repairs of this character have to be effected in the "coil" loaded cable, no noticeable impairment in the quality of the speech will result if the coil spacing is disturbed to an extent not exceeding 5 per cent. on either side of the best location from the theoretical point of view. It has been found that when physical conditions impose a variation of not more than 50 per cent. of the spacing for a single coil, no appreciable impairment in the quality of the speech will result provided the deficiency in loading is made up within the next ten loading sections.

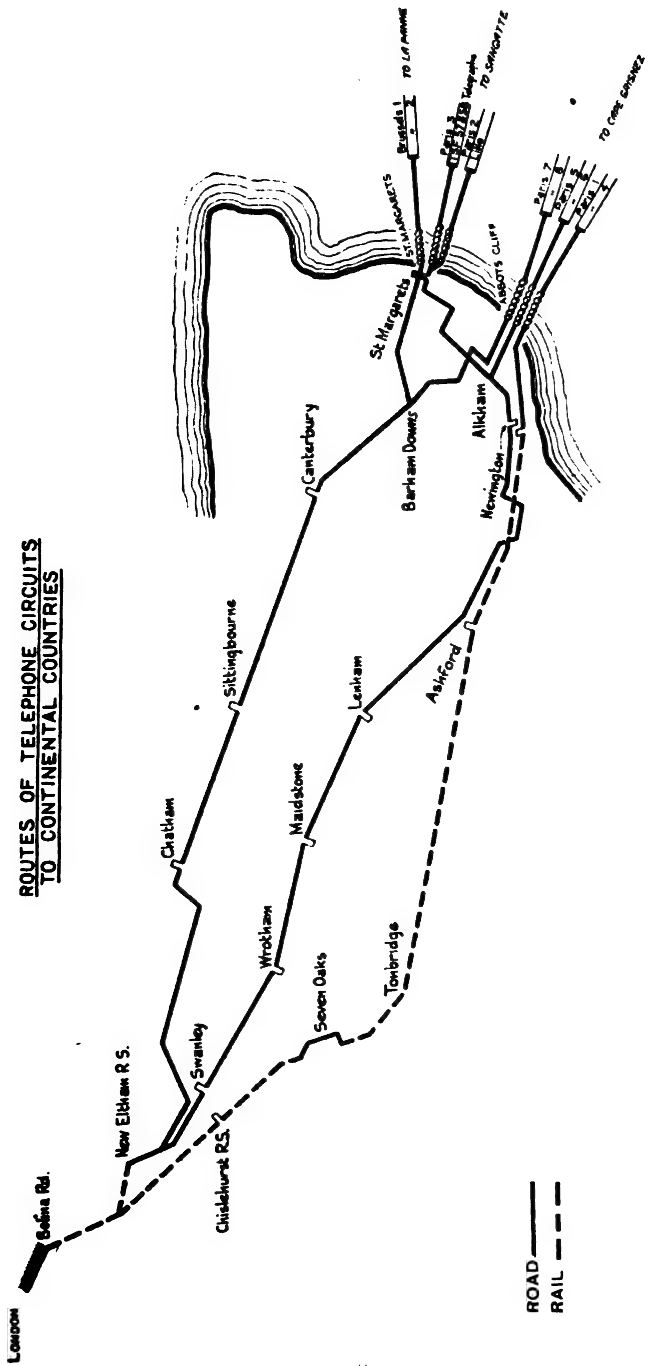

ROUTES OF TELEPHONE CIRCUITS
TO CONTINENTAL COUNTRIES
LONDON
New Eltham R S.
Chislehurst R.S.
Swanley
Seven Oaks
Tonbridge
Wrotham
Chatham
Maidstone
Sittingbourne
Lenham
Ashford
Canterbury
Barham Downs
Newington
Alkham
St Margarets
ST. MARGARETS
ABBOTS CLIFF
TO LA PANNE
TO SANGATTE
TO CAPE GRISNEZ
ROAD
RAIL

FIG. 6.

The frequency with which repairs have been carried out on the existing telephone cables, as shown in the chart Appendix XII., will convey some idea of the importance of this matter.

The investigations that had been made left little doubt concerning the balance of advantages in favour of the "coil" loaded type of cable from the electrical standpoint, but as the expenditure involved was very great, and as it was felt that the main difficulty in connection with this type of cable would be in safely laying the cable at the bottom of the sea, it was considered that special precautions were necessary to ensure that the responsibility for any defects that might be disclosed after it had been laid, should be definitely traced to the responsible party. To afford the necessary protection to the Department, it seemed desirable to stipulate in the specification that the manufacturers of the cable should also undertake to lay it, and to hand it over *in situ*. This course was approved by the Postmaster-General, and the invitations to tender were issued on these lines. The conditions were accepted by Mersrs. Siemens Bros. & Co., who were the successful tenderers.

The routes of the land lines serving the telephone cables to continental countries are shown in Fig. 6.

Description of the Laying of the Cable.

Mr. W. Dieselhorst was entrusted by Messrs. Siemens Bros. with the actual operation of laying the cable, and Mr. F. Pollard, Submarine Superintendent, Dover, was detailed to watch the interests of the Post Office.

The cable ship *Faraday* was employed for the purpose of laying the cable. As a precautionary measure, the ordinary paying-out drum had been replaced by one of larger diameter, and fleeting-knives were also provided in order to prevent the cable from over-riding. The new drum was 8 ft. in diameter, and 30 in. wide, and three fleeting-knives were fitted side by side to this rather wide drum to prevent any undue pressure on the loading coils, which would be caused if two turns on the drum were fleeted by one knife only (Figs. 7 and 8). It was further decided to pay the cable out without passing it under the dynamometer wheel as is usually the case where deep-water cables are concerned. All bends were avoided by letting the lead from the tank go on to the upper part of the drum, and an open wood trough was fixed from the cable tank to the drum to support and protect the cable between these points (Fig. 9). Since the upper part of the drum is nearly in line with the stern sheave there was no extra bending of the cable over any intermediate supporting sheaves after it had left the drum. The stern sheave on board the *Faraday*, which has a diameter of 4 ft., can be swung out at will to any angle, and this was found to be exceedingly serviceable when turning the ship round at right angles near Abbot's Cliff, and again when the French coast was reached.

The cable was paid into the *Faraday's* tank on the 2nd and 3rd of

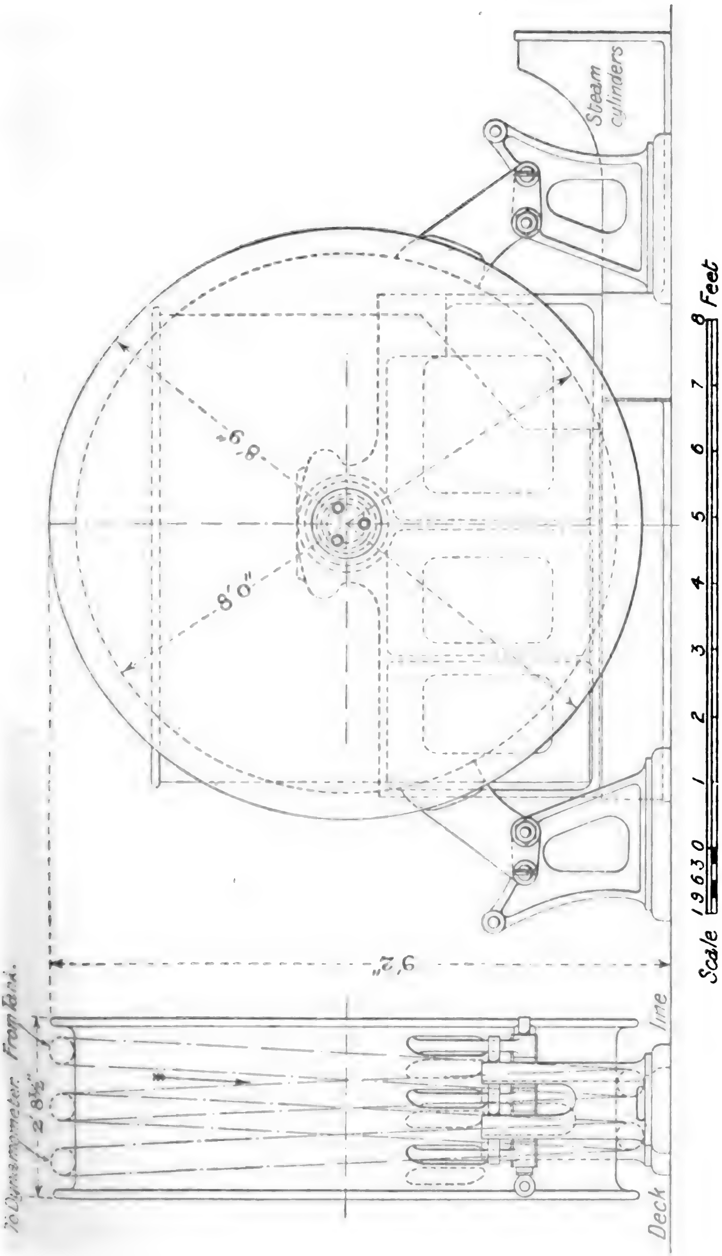


FIG. 7.—Diagram showing Dimensions of C.S. *Faraday's* Paying-out Drum with Fleeting-knives.

May, 1910, and the ship left Woolwich on the 4th with the official representative of the Post Office on board. A large party of gentlemen—from this country and Germany—especially interested in telephone enterprise embarked on the *Faraday* as guests of Messrs. Siemens. Operations were commenced at 5 a.m on May 5, 1910, by dropping a buoy, to which the shore end was attached, overboard about ½ mile from the South Eastern Railway Company's retaining wall south of the tunnel works. For some distance the cable was laid parallel to the British coast, until a point was reached opposite the landing-point, when the ship's bow was turned towards the French coast.

Preparations had been made by the British Administration to assist the *Faraday* in keeping her course, and for this purpose buoys had been placed at intervals by H.M.T.S. *Monarch*, the positions of which were recorded on a chart supplied to the contractors. The importance of these preliminary arrangements cannot be exaggerated. The English Channel is becoming very congested as regards cable routes, and in order to faciliate the maintenance of new telephone cables some alterations in the routes of old cables had been effected on the English coast, so as to avoid the laying of the new cable over old ones—these alterations are shown in the chart (Appendix XII.). This chart does not by any means show the whole of the cross-channel cables at this point, there being nine cables in all.

The day being fairly clear and the sea smooth, the *Faraday* was easily able to follow the line of buoys, and the laying of the cable went off without a hitch, but a brisk wind sprung up late in the afternoon, and the *Faraday* had a somewhat rough passage back. It was not possible for the *Faraday* to approach nearer than 1½ miles to the French landing-place, as the coast shelves out very gradually. Therefore, when the ship was about that distance from the coast, the course was altered, and the remaining portion of cable paid overboard approximately parallel to the coast.

The landing of the shore ends was undertaken by Mr. F. Pollard, Submarine Superintendent, on May 18, 1910. H.M.T.S. *Alert* was employed for this purpose, and the work commenced at 5 a.m. The shore end on the English coast was first picked up, and the cable coiled into the ship's forward tank. The *Alert* then steamed in as close to the shore as her draught would allow and anchored. A raft was made, and the shore end paid out on to it. The raft was then towed ashore by means of a warp rope, the cable being paid out into the water. This work was completed at 11 a.m., and the *Alert* at once proceeded to the French coast, where the section of cable parallel to the coast was picked up. When the tide permitted, the ship steamed in towards the French shore paying out the cable. A short length provided in excess of the actual length required to reach the shore was cut off and the remainder of the cable was paid overboard at a distance of about 350 yards from the cable hut. When the tide receded this section of the cable was uncovered, and it was possible to carry the end to the cable hut.

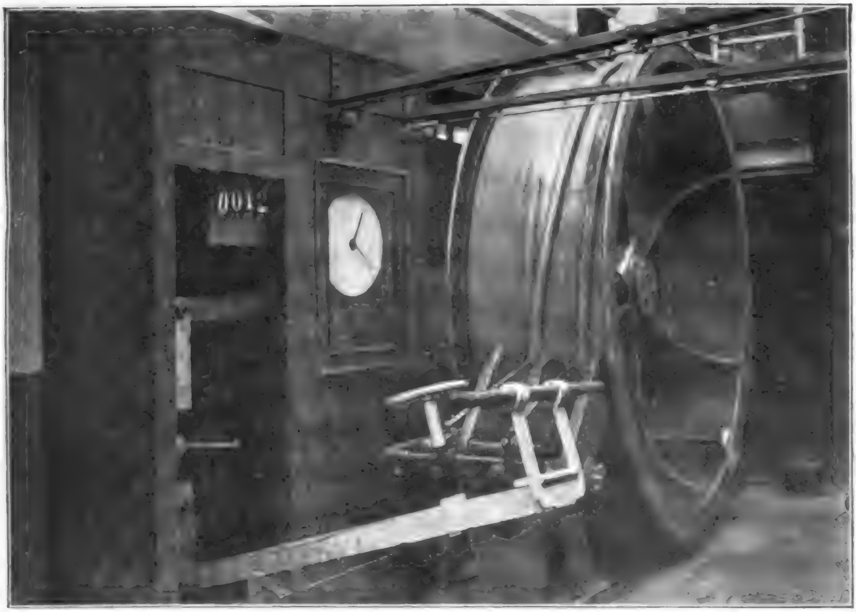


FIG. 8.—C.S. *Faraday's* Paying-out Drum with Fleeting-knives.

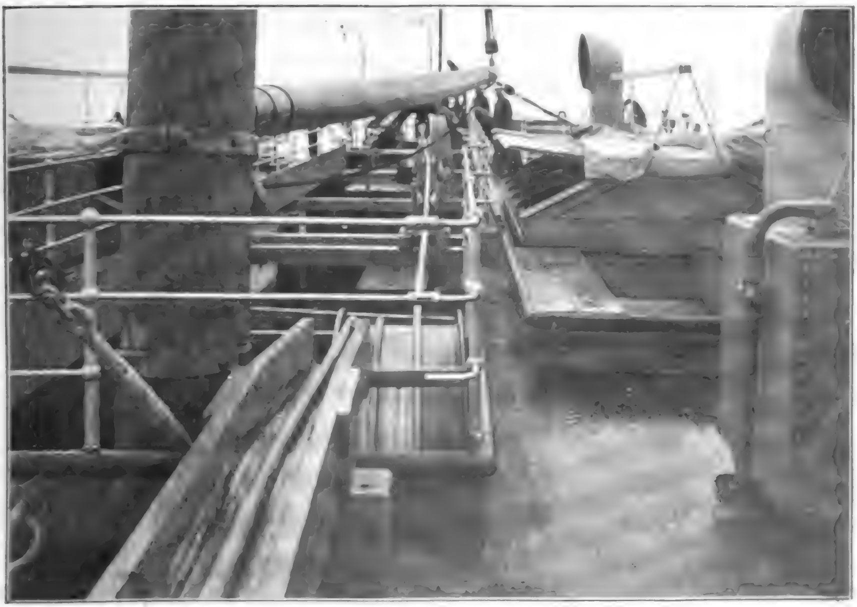


FIG. 9.—Cable passing through Troughing and over Paying-out Drum to Stern Sheaves.

FIG. 10.—Easing a Loading Coil over the Sheaves.

Since the bow sheaves of the *Alert* are only 2½ ft. in diameter, it was thought advisable to take special precautions in picking up, and taking the portions of the cable containing the loading coils on board, and again in paying them out, so as to ensure that the loading coils should not suffer any damage. For this reason loading coil sections were not allowed to ride on the bow sheaves, but tackle was fixed to a derrick, and the coils were carefully lifted over the sheaves. However, in the case of the coils in the section of the cable in excess of that required for present needs, the opportunity was seized to ascertain whether the coils would be injured if allowed to pass over the *Alert's* sheaves in the absence of the precautions referred to. This portion of the cable therefore, was hauled aboard in the usual manner, and a speech test was then made on the four conductors of the cable (the ends being looped at the English end) to ascertain whether any damage had resulted. No injury was disclosed in the test; in fact, everything appeared in the best of order.

The cable has been under continuous observation since it was laid and a large number of tests have been carried out. Particulars of some of them are given in Appendix XIII. It has fortunately been possible to obtain independent testimony on the question of the increase in the range, and in the improvement in the quality of speech transmitted by means of the loaded cable as compared with a similar cable unloaded. Speech tests were made in July last by Messrs. W. R. Cooper, W. Duddell, F.R.S., W. Judd, and J. E. Kingsbury, and the results are interesting. The cable was looped at the French end (Cape Grisnez), and the English ends were connected to two telephone sets—one installed in the cable hut at Abbot's Cliff, and the other in the coastguard look-out shelter some 100 ft. distant. Graduated artificial cables were provided so that the listener at the cable-hut could insert various values of the "standard" cable into the circuit, until his own limit of satisfactory audibility was reached. It was possible to insert the "standard" cable values equally at the two ends of the cable (*i.e.*, so as to form a symmetrical circuit in relation to the submarine cable), or unequally, as desired. The results shown in the table on page 330 were obtained.

The mean gain by the use of the new cable is therefore 17 miles of "standard" cable for the standard of audibility accepted as commercial by the four observers named. When the cables were alone in circuit some of the observers noticed that in the case of the new cable there was a distinct improvement in the quality of the speech as compared with the old cable.

The employment of unloaded 800-lb. copper aerial conductors such as are in use for the most important long-distance trunk circuits in this country, will render it possible for very satisfactory conversations to take place from call-boxes between centres in England and on the Continent when the added distances from the ends of the cable do not exceed 1,700 miles: that is to say, with land-lines of this description well-maintained conversations between London and Astrakhan on the

Caspian Sea would be possible. In his inaugural address to the Institution,* Sir John Gavey included a table of equivalents of the various types of unloaded conductors. It may be assumed that in practice

Observer Listening.	Old Cable. Added Length of Standard Cable.	New Cable. Added Length of Standard Cable.	Gain by New Cable.
			Miles.
W. R. Cooper ...	24 miles symmetrical	48 miles symmetrical	24
		40 miles symmetrical	16
W. Duddell ...	24 miles symmetrical	* 50 miles symmetrical	26
		* 55 miles at one end	21
W. Judd	26 miles symmetrical	40 miles symmetrical	14
J. E. Kingsbury...	26 miles symmetrical	40 miles symmetrical	14

* As breakdown limits of hearing.

aerial conductors of the smaller gauges can be improved by loading twofold, and the conductors in cables threefold, so that it is not difficult to determine the centres between which the new Anglo-French telephone cable will provide communication, assuming that a particular type of conductor is employed to complete the circuit.

Conclusion.

Although great improvement in speech transmission has resulted from this latest type of cable, yet the new Anglo-French cable cannot by any means be regarded as the last word on submarine telephone cables. An attempt has been made in this paper to place on record some of the steps taken in developing the art of long-distance telephony, but many problems remain to be solved, and they do not appear to be of a character likely to yield a ready answer to those seeking their solution. As in the past, the co-operation of the mathematician, physicist, engineer, and manufacturer are still needed if an announcement is to be made in this theatre twenty years hence that the progress in the art of telephony has resulted in an increase of efficiency comparable with that which has been achieved during the past twenty years, and which it has been my pleasure to record here to-night.

The practical engineer recognises fully how much he is indebted to the mathematical investigations of Messrs. Heaviside, Pupin,† Perry,‡

* *Journal of the Institution of Electrical Engineers*, vol. 36, p. 28, 1905.
† *Transactions of the American Institute of Electrical Engineers*, vol. 16, p. 93, 1899.
‡ *Philosophical Magazine*, vol. 36, p. 222, 1893.

Kennelly,* and others, in respect of the progress made in the past. There are to-day a number of earnest workers, both in this country and in foreign lands, who are sparing no efforts to render possible the transmission of speech from any one point of the habitable globe to any other. In America, Mr. J. J. Carty, of the American Telephone and Telegraph Company, is engaged in solving the problem of putting the towns of the East Coast of the United States of America into communication with the towns on the West Coast of that great continent. Recently, at Paris, he stated that he hoped to establish satisfactory communication between New York and Denver (distance, 1,700 miles) during the autumn of this year. Experimental investigations are being carried out by, amongst others, M. Devaux-Charbonnel in France, Drs. Breisig and Ebeling in Germany, M. Béla Gáti in Hungary, and here in our midst Mr. Gill and his able staff of assistants are vying with Mr. H. R. Kempe, the electrician, and the capable staff engaged on this work at the General Post Office.

I feel that the most important matter to which attention should be turned at the present time is that connected with the measures which should be adopted to ensure that the scientific and practical results obtained by the investigators in these widely separated centres shall be in such a form as to be easily comparable. A scientific spirit is abroad, and it has been agreed to abandon standards of commerce and to adopt those of the laboratory to record values affecting the efficiency of telephone circuits. So far so good. The problem, however, is one containing many complexities, and the final results, I think, must be measured from the point of view of the non-scientific user. It would appear, therefore, that it is not possible to deal with telephonic transmission from the consideration of the attenuation constant in its mathematical aspect alone, but it is necessary to take into consideration its practical aspect as affecting audition. In the early part of September, 1910, I had the privilege of taking part in experiments at Paris arranged by Dr. Breisig and M. Devaux-Charbonnel, which consisted in talking over actual telephone circuits, into which, in turn, artificial cables were introduced of three different types designed to reproduce conditions representing—

(*a*) Aerial wires.
(*b*) Unloaded cables.
(*c*) Loaded cables.

The talking circuits were so arranged that in each case the total attenuation was by mathematical calculation exactly the same. These experiments showed that the quality and volume in audition under the three different cases were by no means in agreement. Clearly, then, for comparative purposes, it seems to be most desirable not only that the conditions with regard to the circuit arrangements, including terminal conditions, shall be identical, but that all those who are

* *Transactions of the International Electrical Congress*, St. Louis, 1904, vol. 1, p. 68.

engaged in this important investigation should employ, in connection with their experiments for measuring audition, apparatus manufactured to the same specification and compared with an international standard. It is hoped that this result may have been attained as a consequence of the recent International Conference at Paris.

My thanks are specially due to the Postmaster-General for permitting me to place before our members much of the information contained in the official records of the Engineering Department. Further, I have been encouraged to prepare this paper because I learnt from Mr. Herbert Samuel himself that it was his wish that the public shall be made aware of the work done in the departments which he directs. We recognise that the efforts to effect improvements would be of no avail without the very practical assistance we receive from manufacturers, to whom I tender the thanks of the Post Office Engineering Department, and in the matters dealt with in these papers there has been no exception to the general rule. I cannot close my remarks without making some acknowledgment of my indebtedness to Mr. A. J. Stubbs, the gentlemen I have already named, and many other members of my staff, for the valuable assistance received, not only in connection with the work which has been described, but also in the preparation of the information contained in this paper.

APPENDIX I.

Map of England and Part of Ireland showing Important Submarine Telephone Cables in British Waters.

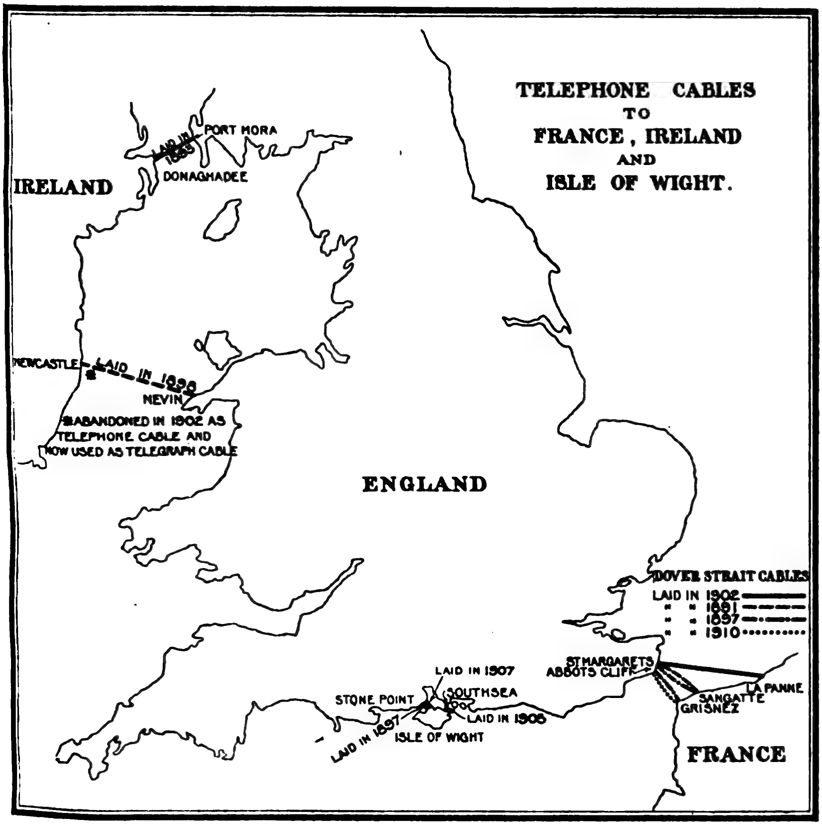


Fig. 11.

APPENDIX II.

Short Description of the First Anglo-French Telephone Cable.

(Fig. 13, Appendix VI.)

Opened to the Public April 1, 1891.

This was a 4-core cable differing but little from those in use at the time for telegraphic purposes, except in the size of the cores. Each core consisted of a stranded copper conductor formed of 7 equal wires, having a total weight of 160 lbs. per knot, covered with 300 lbs. of gutta percha per knot. The extreme diameters of the copper strand (d) and of the gutta percha covering (D) were 0·108 and 0·390 in. respectively, giving a ratio $\frac{D}{d} = 3{\cdot}61$.

The measured resistance of the conductor at 75° F. was 7·453 ohms, and the measured electrostatic capacity 0·275 microfarad per knot. The sheathing consisted of 16 galvanised iron wires, each 0·280 in. in diameter, put on with a lay of 18 in., and the external diameter of the finished cable was about 2·2 in.

APPENDIX III.

Description of the Air-space Type of Submarine Telephone Cable.

In 1895 Messrs. Willoughby Smith and W. P. Granville took out a patent for a type of submarine cable core which was designed to combine the advantages of an "air-space" cable with low capacity, and of gutta percha insulation with its well-known durability and impermeability to moisture. The method of building up the core will be obvious from Appendix VI., Fig. 15, which represents a section of the "air-space" cable laid in 1898 between Nevin, North Wales, and Newcastle, co. Wicklow. Each conductor consists of a central wire 50 mils in diameter surrounded by ten wires each of 22 mils diameter. Two conductors were covered with gutta percha so as to form a crescent-shaped semicircular segment, as shown in the Fig. Two such crescent-shaped strips were then "laid" together with a helical twist and doubly covered with gutta percha to a diameter of 0·580 in., forming a tubular core. The weight per knot of each of the four conductors was 138 lbs., and the total weight of gutta percha 552 lbs. per knot, that is, equal to the total weight of copper. The conductor resistance was 8·515 ohms per knot at 75° F., and the wire-to-wire capacity of diagonal pairs 0·1016 microfarad per knot. This capacity is about 19 per cent. less than the mutual capacity of two conductors in the ordinary Post Office type of submarine telephone cable. To prevent flooding of the whole cable in case of damage at any point the core was made solid at the joints.

APPENDIX IV.

Particulars of three Submarine Cables connecting Nevin (Wales) and Newcastle (Ireland).

Cable.	Gutta Percha. Weight per Knot.	Copper.		R. Standard Ohms. Per Knot.	K. Wire to Earth. Per Knot.	L. Millihenries. Per Knot.	Insulation at 75° F.	Total Length of Cable.
		Weight per Knot.	No. of Strands.					
	Lbs.	Lbs.			Microfarads.			Knots.
No. 1 telegraph cable ...	150	107	7/22	11·145	0·3333	2·195	Not less than 500 nor more than 1,000 megohms	56·078
No. 2 telegraph cable ...	150	107	7/22	11·145	0·3333	2·195	Ditto	60·630
Air-space type of submarine telephone cable ...	552 *	138	10 wires 22 mils diameter stranded round a central wire 50 mils diameter	8·515	0·1974	2·96 diagonal wires 2·13 adjacent wires	988	57·123

* Total weight per knot for the four conductors.

APPENDIX V.

Particulars of Types of Submarine Telephone Cables proposed for the Anglo-French Service.

I. Hammered Segmental Conductors with Protuberances: Paper Insulation for Core.

(Fig. 14, Appendix VI.)

Weight of conductor, 900 lbs. per knot.
Each conductor $\frac{7}{0}$ S.W.G. to be covered longitudinally with one layer of paper 1·75 in. wide and 0·015 in. thick.
Whipped with 15 lea 2-ply yarn $\frac{15}{16}$ in. lay.
The two conductors so insulated twisted together (about 3 ft. lay) with protuberances adjacent and opposite, with 9 papers each $\frac{5}{8}$ in. wide and 0·012 in. thick between them.
The pair to be lapped with three layers of paper 0·006 in. thick.
Six paper strings laid round $2\frac{1}{4}$ in. lay.
Double proof tape one coat, $1\frac{1}{4}$ in., $\frac{1}{4}$ in. lap.
Layer of vulcanised indiarubber, 0·047 in. thick.
Layer of double proof tape to a diameter of 1 in.
Thin coating of Chatterton's compound and gutta percha $\frac{1}{10}$ in. thick up to a diameter of $\frac{1}{2}$ in.
One layer of brass tape, $\frac{1}{8}$ in. lap.
Thin coating of Chatterton and covering of gutta percha 0·04 in. thick.
Coating of hemp, 25 lbs.
Waterproof separation from gutta percha covering.
Weight of gutta percha, 1,400 lbs. per knot.
Sheathed with 18/0·280 in. Post Office wire.
Two coats 3-ply Post Office hemp.
Diameter overall, 2·22 in.
Weight per knot, 298 cwt.

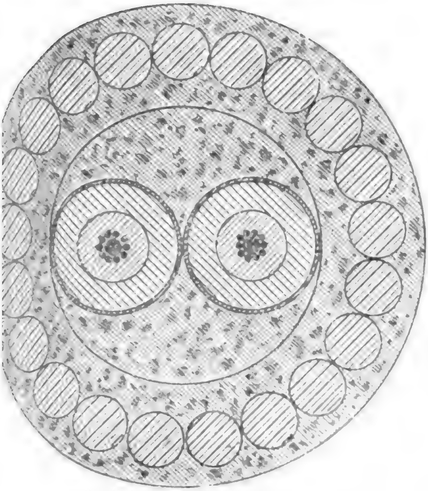
II. Composite Core Submarine Telephone Cable (Paper and Gutta Percha).

(Fig. 12, Appendix VI.)

Each conductor 500 lbs. per knot, 12-strand $\left\{ \begin{array}{l} 1 \times 0·104 \text{ in.} \\ 11 \times 0·0385 \text{ in.} \end{array} \right.$

One longitudinal air-space paper.
Six spiral layers of paper (with gap).
One spiral layer of paper (without gap) to 0·43.
Gutta percha ($\frac{1}{8}$ in. thick) to 0·68 in. (572 lbs. per knot).
Actual capacity, 0·139 microfarad per knot (wire to earth).
Each core brass taped, 2 cores stranded, wormed, and served jute yarn.
Sheathed 21 × 0·280 galvanised steel, double jute served outside.

APPENDIX VI.



12.—Composite Core. Paper and Gutta Percha.
500 lbs. copper, 572 lbs. gutta percha.
(Full size.)

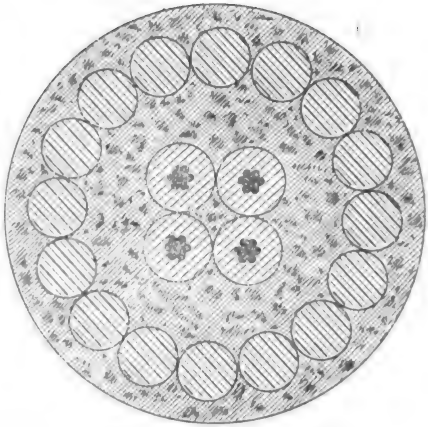


FIG. 13.—Anglo-French (1891) Cable,
Gutta Percha Core.
16c lbs. copper, 300 lbs. gutta percha.
(Full size.)

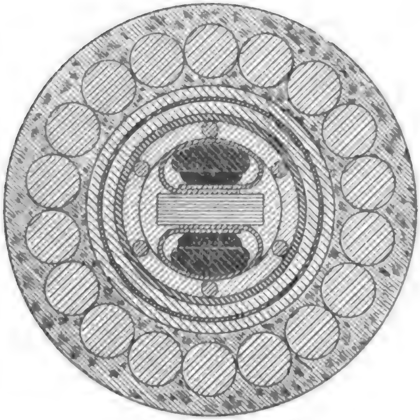


FIG. 14.—Composite Core. Paper, India Rubber, and Gutta Percha.
900 lbs. copper, 280 lbs. india rubber, 1,400 lbs. gutta percha. (Per knot.)
(Full size.)

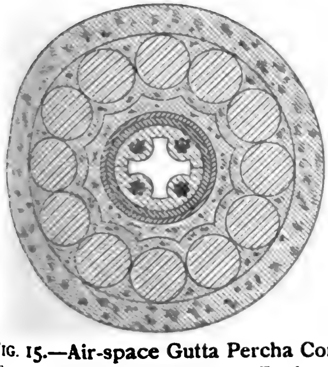


FIG. 15.—Air-space Gutta Percha Core.
12 lbs. copper, 552 lbs. gutta percha. (Total weights.)
(Full size.)

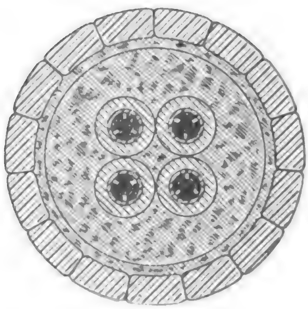


FIG. 16.—"Continuously" Loaded Core.
Gutta Percha.
285 lbs. copper, 180 lbs. gutta percha.
(Full size.)

Sections of Submarine Telephone Cables that have been adopted or Proposed.

APPENDIX VIA.

ESTIMATED COST PER CIRCUIT OF DIFFERENT TYPES OF SUBMARINE TELEPHONE CABLES ASSUMING COPPER AT £75 PER TON AND GUTTA PERCHA AT £560 PER TON.

Type of Cable.	Estimated Cost.		Attenuation Constant (β) per Knot.
	Per Knot.	Per Circuit per Knot.	
	£	£	
Paper and gutta percha (2-core) 500 lbs. copper, 572 lbs. gutta percha	1,055	1,055	0·01401
Anglo-French loaded cable (4-core) 160 lbs. copper, 300 lbs. gutta percha	520	260	0·01660
Composite core. Paper + india-rubber + gutta percha (2-core) 900 lbs. copper, 280 lbs. india-rubber, 1,400 lbs. gutta percha ...	1,145	1,145	0·03050
Air-space gutta percha (4-core) 552 lbs. copper, 552 lbs. gutta percha	285	143	0·05170
Danish loaded gutta percha (4-core) 285 lbs. copper, 180 lbs. gutta percha	385	193	0·02960

The above cables do not necessarily represent the most economical utilisation of the materials of which they are constructed. Unfortunately the prices of the two principal materials used in submarine cables are subject to extraordinary fluctuations, and this makes it difficult to adopt a standard design for a given attenuation constant. It will be observed that the costs of the cables have not been based on current prices of copper and gutta percha.

APPENDIX VIb.

Statement showing Approximate Costs of Cables of Different Types, but of Equal Telephonic Efficiency ($\beta = 0{\cdot}0296$).

Type of Cable.	Cost. Copper, £75 per ton. Gutta percha, £560 per ton.	
	Whole Cable per Knot.	Per Circuit per knot.
	£	£
Anglo-French loaded cable,* 4 cores ... Copper, 46 lbs. per mile. Gutta percha, 116 lbs. per knot.	284	142
Danish loaded cable, 4 cores ... ... Copper, 285 lbs. per mile. Gutta percha, 180 lbs. per knot.	380	190
Paper and gutta percha, 2 cores (unloaded) Copper, 390 lbs. per mile. Gutta percha, 530 lbs. per knot.	977	977

* The proportion of copper and gutta percha in this cable would not be followed in any future type of cable; the amount of gutta percha would be considerably less, and the amount of copper more. This would make the cost of the whole cable very much less.

APPENDIX VII.

SOME FOREIGN "CONTINUOUSLY LOADED" SUBMARINE CABLES.*

	Cable.	Date of Laying.	Length in Knots.	Number of Conductors.	Copper Square Inch.	Wrapping of Iron Wire.	Insulation Thickness in Inches.	Lead Sheath.	Resistance in Ohms per Knot of Conductor.		Capacity Farads per Knot of Conductor.		Self-induction Millihenries per Knot of Conductor.		Old Formula (Preece) $C'\gamma$.	β per Knot $n=900$.
									γ Continuous Current.	ω Alternating Current $n = (900)$.	C' Continuous Current.	C Alternating Current.	Prepared (Wrapped with Iron Wire).	Without Iron Wire.		
A	Elsinore-Helsingborg ...	Nov., 1902	2·85	4	0·0054	Mils. 7·88	Gutta percha 0·323	No	† 8·49	† 8·79	† 0·324 × 10—6	† 0·3030 × 10—6	† 4·92	† 1·100	2·750 × 10—6	0·0340
B	Fehmern-Laaland	Jan., 1903	10·38	4	0·0155	11·82	Impregnated paper	Yes	3·18	4·79	0·301 „	0·2660 „	4·65	0·850	1·075 „	0·0184
C	Greetsiel (Emden) Borkum	Spring, 1903	15·85	4	0·0054	11·82	Air-space paper	Yes	9·03	11·08	0·138 „	(0·1243) „	7·41	1·240	1·335 „	0·0225
D	Cuxhaven-Heligoland ...	Autumn, 1903	40·50	2+ 2/2	0·0186	11·82	Solid paper	Yes	2·53	3·38	0·170 „	(0·1490) „	3·98	0·595	0·427 „	0·0104
E	Seeland-Samsö-Jutland ...	July, 1904	8·93 + 11·02	4	0·0124	3 × 7·88	Gutta percha 0·355	No	3·98	4·18	0·500 „	0·4460 „	8·08	(0·900)	1·970 „	0·0156

The figures in brackets are, however, interpolated or approximately stated.

* See *Elektrotechnische Zeitschrift*, vol. 29, p. 586, 1908, and also *Journal Télégraphique*, vol. 29, p. 187, 1905. † The figures refer to single-wire values.

"CONTINUOUSLY" LOADED CABLES.

(Krarup Type.)

The first "continuously" loaded cable having the copper conductor wrapped with a layer of 0·008-in. iron wire on Krarup's plan appears to have been that laid by the Danish Government, in November, 1902, between Elsinore and Helsingborg.* Mechanical and electrical data of this cable are given in the table. The dielectric was gutta percha, and, except in respect of the iron wrapping, the cable did not differ materially from the ordinary type of submarine cable. This was followed, as will be seen from the table, by various paper-insulated cables having the conductors wrapped with a single layer of 0·012-in. iron wire. The cable shown in Fig. 16, Appendix VI., is that laid in July, 1904, and is distinguished by the letter E in the table. Each copper conductor consists of a central wire about 0·089 in. in diameter surrounded by three copper strips each 0·094 in. wide and 0·020 in. thick. The sectional area of the copper is approximately 0·0124 sq. in., and the weight per knot 285 lbs. The iron wrapping consists of three layers of 0·008-in. wire, and the insulator is gutta percha having an external diameter of 0·354 in. The four cores are laid up with an inner serving of tanned jute and an outer serving of tarred jute yarn to a diameter of 1·18 in., and sheathed with 15 galvanised iron wires of roughly trapezoidal section. The external covering appears to be the usual tarred yarn and compound.

The electrical constants of the cable per knot from Mr. Krarup's figures are as follows:—

Resistance. Ohms per Knot of Conductor.		Capacity. Microfarads per Knot of Conductor.		Self Inductance. Millihenries per Knot.	
Steady Current.	Alternating Current, $n = 900$.	Steady Current.	Alternating Current.	With Iron.	Without Iron.
3·971	4·175	0·4983	0·4454	8·07	0·93

Of the paper-insulated lead-covered cables the Dano-German telephone cable laid between Fehmern and Laaland in 1907 may be taken as representative. The copper conductor with its triple soft iron wire wrapping is precisely similar to that used in the Seeland-Samsö-Jutland cable described above. The insulator consists of paper cord laid on in an open spiral followed by a close wrapping of paper ribbon up to a diameter of 0·303 in. Four of the cores so formed are stranded together with the necessary worming and then covered with paper to a diameter of 0·787 in. The diagonal distance apart of the cores, centre to

* *Moderne Telefonkabler*, by C. E. Krarup. *Elektroteknikeren*, December 10, 1904.

centre, is 0·413 in. The core after being thoroughly dried is next sheathed with two layers of lead alloyed with 3 per cent. of tin, each layer being 0·055 in. thick. The lead sheath is seamless, water-tight, and continuous throughout the entire length of the core. Outside the lead sheath is a double layer of asphalted paper and a layer of jute and compound. The armour consists of 13 galvanised iron wires or strips of trapezoidal section $\left(\frac{0·315 + 0·252}{2} \times 0·157 \text{ sq. in.}\right)$, and over this is a double layer of jute and compound.

To prevent the destruction of the cable by the puncture of the lead sheath at any point solid plugs 1 metre (3·28 ft.) long are inserted at every 150 metres (164 yards).

Resistance per knot of loop, 8·924 ohms	Continuous current.
Capacity per knot of loop, 0·0872 microfarad... ...	
Capacity per knot of loop, 0·0770 microfarad... ...	Alternating current.

Inductance per knot of loop, 18·26 to 18·09 millihenries.

APPENDIX VIII.

Formulæ for Calculating Attenuation Constant of "Continuously" Loaded Circuits.

Values of the inductances obtained by the employment of a continuous solid iron envelope over copper conductors are calculated from the formula—

$$L = 4\left[\log\frac{2d}{r} + \frac{1}{4} + (\mu - 1)\log\frac{r+t}{r}\right]10^{-4} \text{ per kilometre,}$$

where—

L = inductance in henries.
$2d$ = distance between centre conductors in cms.
r = radius of each conductor in cms.
μ = permeability = 120.
t = thickness of iron covering.

In the case of the Danish cable tested by Mr. Martin (Cable E, Appendix VII.)—

$$2d = 1{\cdot}275 \text{ cms.}$$
$$r = 0{\cdot}16 \quad ,,$$
$$t = 0{\cdot}06 \quad ,,$$

Then $L = 0{\cdot}016$ henries per kilometre.

The values of the inductances* obtained by the employment of a wire-wound continuous envelope over the copper conductors—

$$L = \left[2\pi\left(\frac{1}{R} + \frac{1}{R_2} + \dots + \frac{1}{R_v}\right)\frac{r^2}{2\,r + g}\left(\frac{\mu}{1 + a} + f\right) + 2\log\frac{2\,r_3 - r_2}{r_2}\right]10^{-4} \text{ henries per km. of loop,}$$

where—

$$f = \frac{4}{\pi} - 1 + \frac{2\,g}{\pi\,r},$$

and—

$$a = \mu\,\frac{r\sqrt{g\,r}}{8\,\pi\,R^2\tan^{-1}\cdot\dfrac{r}{\sqrt{g\,r}}}.$$

r = radius of iron wire in cms.
v = number of layers of iron wire.
g = gap between convolutions of iron wire in cms.
R_1 = mean radius of first layer of iron wire in cms.
R_2 = mean radius of second layer of iron wire in cms.
R_3 = mean radius of third layer of iron wire in cms.

* This is from Larsen's formula (*Elektrotechnische Zeitschrift*, vol. 29, p. 1031, equation (17). The coefficient 2 is wanting in the expression as there found, because the author reckons inductance, etc., "für 1 km. einfache Leitung."

$R = \frac{1}{v}(R_1 + R_2 + R_3)$.

r_2 = outer radius of iron wrapping in cms.

r_3 = half the distance in cms. between centres of conductors.

μ = permeability of iron.

In the case of the Danish cable tested by Mr. Martin (Cable E, Appendix VII.)—

$$
\begin{aligned}
r &= 0{\cdot}01 \text{ cms.}\\
v &= 3.\\
g &= 0{\cdot}005 \text{ cms.}\\
R_1 &= 0{\cdot}17 \quad \text{,,}\\
R_2 &= 0{\cdot}19 \quad \text{,,}\\
R_3 &= 0{\cdot}21 \quad \text{,,}\\
r_2 &= 0{\cdot}22 \quad \text{,,}\\
r_3 &= 0{\cdot}6363 \text{ ,,}\\
\mu &= 120.\\
S &= 12 \times 10^{-6}
\end{aligned}
$$

(This value for leakance is adopted as being 100 times the capacity.)

Then $L = 0{\cdot}0102$ henries/km. of loop.

Note.

In the tables of Appendices IX. and IXA. effective resistances are calculated. The following expression * has been used :—

Extra resistance due to eddies in the iron is—

$$\Delta w = 10^{-13}\, 8\, \pi^4 \left(\frac{1}{R_1} + \frac{1}{R_2} + \dots \frac{1}{R_v}\right) \frac{1}{\rho} \left(\frac{\mu}{1 + a}\right)^2 n^2 \, \frac{r^4}{2r + g}$$

ohms/km. of loop,

where—

ρ = specific resistance of iron in ohms/sq. cm./cm.

n = frequency in periods per second,

and lengths are in cms.

Further, the hysteresis loss is taken as half of the eddy-current loss in the iron. The reason for so doing lies in this: that Larsen † finds such is very nearly the value of the hysteresis loss at 765 periods per second for a cable whose separate cores are very nearly similar to those of the actual cable, but which lie close together, instead of being separated as in the quad-pair arrangement to which the tables of Appendices IX. and IXA. refer.

Finally, the capacity of the cable, used in the tables to calculate β, is found from the usual expression, substituting for the radius of the copper the other radius of the iron wrapping.

* Larsen, *Elektrotechnische Zeitschrift*, vol. 29, p. 1032, equation (39).

† *Elektrotechnische Zeitschrift*, vol. 29, p. 1033, Beispiel 2.

APPENDIX IX.

CONSTANTS OF A "CONTINUOUSLY" LOADED DANISH TELEPHONE CABLE COMPARED WITH THE CONSTANTS OF THE SAME CABLE WITHOUT LOADING AND WITH COIL LOADING.

Cable Core Details.			Constants per Knot of Loop at 750 p.p.s.					Attenuation Constant β.			
Overall Diameter of Copper.	Loading.	Overall Diameter of Gutta Percha.	Resistance Ohms.		Inductance in Millihenries.	Capacity in Microfarads.	Leakance in Mhos.	Per Kilometre.	Per Statute Mile.	Per Nautical Mile.	
			Direct Current.	750 p.p.s.						Calculated.	Observed.
Mils.		Mils.									
126	Three layers of 7·88 mils iron wire 101·5 turns per inch ...	355	7·96	8·88	19·00	0·253	$2·4 \times 10^{-5}$	0·0106	0·0171	0·0197	0·0296
126	Unloaded	355*	7·96	7·96	2·00	0·175	$2·4 \times 10^{-5}$	0·0199	0·0320	0·0369	—
126	Coils of 100 m.h. every 1·075 knots ... ... Steady Current resistance, 2·25 ohms Resistance at 750 p.p.s., 6 ohms	335†	10·06	13·55	95·00	0·186	$2·4 \times 10^{-5}$	0·0080	0·0128	0·0148	—

* Space occupied by iron in first example filled with gutta percha.
† Weight of gutta percha same as in first example.

APPENDIX IXA. (*Amended*).

CONSTANTS OF THE ANGLO-FRENCH COIL LOADED TELEPHONE CABLE COMPARED WITH THE CONSTANTS OF THE SAME CABLE WITHOUT LOADING AND CONTINUOUSLY LOADED.

Cable Core Details.			Constants per Knot of Loop.				Attenuation Constant.				
Overall Diameter of Copper.	Loading.	Over-all Diameter of Gutta Percha.	Resistance. Ohms.		Direct Current		Per Kilometre.	Per Statute Mile.	Per Nautical Mile.		Characteristic Impedance = Zo.
			Direct Current.	750 p.p.s.	Inductance in Millihenries.	Capacity in Microfarads.			Calculated.	Observed.	
Mils.		Mils.									
106·2	Three layers of 7·88 mils iron wire, 101·5 turns per inch ...	405*	14·95	16·06	22·00	0·181	0·0124	0·0200	0·0230	—	—
106·2	Unloaded	390	14·95	14·95	2·00	0·138	0·0278	0·0447	0·0520	0·0524	—
106·2	Coils of 100 m.h. every knot ... ... Steady current resistance, 2·25 ohms Resistance at 750 p.p.s., 6 ohms	390	17·20	20·90	102·00	0·138	0·0091	0·0147	0·0170	0·0166	$858 \sqrt{0^\circ 54'}$

* Weight of gutta percha same as in Cases 2 and 3. Length of Channel cable = 20 knots.

APPENDIX X.

Mr. H. R. Kempe's Method of Calculating the Attenuation of Loaded Circuits, etc.

The formula—

$$\beta = \sqrt{\tfrac{1}{2}\left[\sqrt{(R^2 + p^2 L^2)(S^2 + p^2 K^2)} + RS - p^2 LK\right]}$$

is not a convenient one for general use, owing to the fact that the value of—

$$\sqrt{(R^2 + p^2 L^2)(S^2 + p^2 K^2)} + RS$$

is, in the majority of cases, so very nearly equal to the numerical value of $p^2 LK$ that the equation cannot be correctly solved unless the terms are worked out to a very large number of places of figures; also it is preferable to express L, K, and S in millihenries (l), microfarads (k), and ohms (ω), rather than in henries, farads, and mhos; also for the cable manufacturer, it is more convenient to deal with a single than with a looped circuit.

The formula in this case becomes—

$$\beta = \frac{\sqrt{k}}{20}\sqrt{\sqrt{R^2 + (5\,l)^2} - 5\,l + \frac{200\,R}{\omega\,k} + 0{\cdot}000128\sqrt{R^2 + (5\,l)^2}} \quad . \quad . \quad (1)$$

The value of $\omega\,k$ for ordinary gutta percha-insulated cores may be taken to be 12,500 approximately, so that—

$$\beta = \frac{\sqrt{k}}{20}\sqrt{\sqrt{R^2 + (5\,l)^2} - 5\,l + 0{\cdot}016\,R + 0{\cdot}000128\sqrt{R^2 + (5\,l)^2}} \quad . \quad (2)$$

R being the conductor resistance r, plus the "effective resistance" ρ of the inductance coils; *i.e.*, $R = r + \rho$.

In the case of well-constructed inductance coils the effective resistance is 6 ohms for every 100 millihenries of inductance, *i.e.*, $\rho = 0{\cdot}06\,l$, so that $R = r + 0{\cdot}06\,l$. Formula (2) is a general one, but when l is larger than R (in numerical value), which is usually the case, then—

$$\beta = \frac{r + .14\,l}{63{\cdot}2}\sqrt{\frac{k}{l}}$$

r being the conductor resistance exclusive of the resistance of the inductance coils.

A minimum value is given to β if $r = 0{\cdot}14\,l$, in which case—

$$\beta = 0{\cdot}01183\sqrt{k\,r},$$

and—

$$l = 7{\cdot}14\,r.$$

These two equations are all that is necessary for calculating the inductance which should be given to a cable to make it most efficient telephonically, and also to determine the value of β under this condition.

It may be remarked that the equation—

$$\beta = 0{\cdot}01183\sqrt{k\,r}$$

indicates that a properly loaded cable, in relation to telephonic efficiency, does not follow a "$k\,r$" but a "$\sqrt{k\,r}$" law, and it also follows that the efficiency is inversely proportional to the length, and not to the square of the length.

The value of the leakance is an important factor, and could this be reduced tenfold, the value of β could be reduced about 40 per cent.; and further, if it were possible to reduce the leakance practically to zero, *i.e.*, to make the insulation practically infinite, then the value of β could be reduced 50 per cent., which is the minimum value which could be given to it without reducing the effective resistance of the coils below 6 ohms per 100 millihenries, a result which has so far proved not to be possible.

In comparing the improvement which can be obtained by loading a cable, the fact that there is a normal inductance must be taken into consideration. This normal inductance is about 1 millihenry per knot approximately, but a number of successful experiments have been made to determine its exact value.

The possible improvement from loading diminishes as the conductor resistance diminishes (since, as pointed out, for best conditions $l = 7{\cdot}14\,r$), thus, the possible improvement for a 1-ohm conductor is but one-half that for a 5-ohm conductor. For long-distance speaking in this country, heavy overhead conductors are necessary not only from the point of view of low resistance, but also in regard to the effect of low insulation resistance, which, owing to climatic conditions, it is impossible to avoid. Loading of such lines would, even if possible, be of comparatively little value.

The following formulæ have been developed, based on general principles, and enable various conditions to be calculated.

Formulæ for Loading Coils.

β = attenuation constant per knot.
W = weight of gutta percha per knot.
w = weight of copper per knot.
n = ratio of weight of copper to weight of gutta percha.
£ = total cost of materials of core.
a = cost per lb. of gutta percha (in £s).
b = cost per lb. of copper (in £s).
k = capacity per knot in microfarads.
r = resistance per knot in ohms.
l = total inductance per knot in millihenries.
n_1 = ratio of effective resistance of inductance in ohms to inductance in millihenries.
d = distance apart of inductances.
l_1 = inductance per coil.

$$r k = \frac{1000\,\beta^2}{n_1 + 0{\cdot}08}$$

$$\beta = \sqrt{\frac{k}{\pounds}\,\frac{a + b\,n}{n} \times 1{\cdot}192\,(n_1 + 0{\cdot}08)}$$

$$\pounds = \frac{k}{\beta^2}\,\frac{a \times b\,n}{n} \times 1{\cdot}192\,(n_1 + 0{\cdot}08) \quad \text{or} \quad = a\,W + b\,w$$

$$n = \frac{w}{W}$$

$$k = \frac{0{\cdot}320}{\log\left(\frac{9{\cdot}076}{n} + 1\right)}$$

$$W = \pounds\,\frac{n}{a + b\,n}$$

$$r = \frac{1192}{W} \quad \text{or} \quad = \frac{1192}{\pounds\,\frac{n}{a + b\,n}}$$

$$l = \frac{R}{n_1 + 0{\cdot}08}$$

$$d = \sqrt{\frac{20}{k\,l}}$$

$$l_1 = \sqrt{\frac{20\,l}{k}} \quad \text{or} \quad = \frac{d}{\sqrt{l}}$$

The cost, as regards the materials of the core (gutta percha and copper), of obtaining a low attenuation constant, increases as the inverse square of the constant, *i.e.*, if we double the length of a cable we double the cost and double the attenuation constant, and to halve this doubled constant the size of the conductor and the thickness of the dielectric must be increased; the cost of this increase would be double that of the original cable, length for length.

Note re *"Standard Cable Equivalent" and Nomenclature.*

The "standard cable equivalent" is, of course, formed on a purely arbitrary basis and has no direct relation to the C.G.S. system, but, on the other hand, the attenuation constant β is based on the C.G.S. units. The actual value of 1 mile of standard cable in terms of β is taken as 0·103 (although there is some doubt now as to this being the correct value). As a practical unit, it is suggested that the "centibeta" might be adopted; thus, instead of saying that the limit of telephonic speech is 47 miles of standard cable, we might say that the limit is—

$$47 \times 0{\cdot}103 \times 100 = 480 \text{ centibetas.}$$

Standard cable boxes might with advantage be adjusted to exact "centibeta" units, though there is at present some difficulty in doing this, owing to the uncertain element of "leakance" at telephonic frequency, coming in.

The word "dampance" might be used as meaning the transmission value of any particular line; thus we should say the "dampance" of the Channel cable—

$$= 34 \text{ centibetas.}$$

The use of such a word as "dampance" is in line with modern practice where we speak of resistance, leakance, reluctance, etc.; "loadance" has been used by Jacob (of Siemens), and probably "insulatance" (for insulation resistance) will follow in due course. The word "improvance," in connection with the improvement in efficiency of a cable by loading, is also a convenient one. "Improvance" by loading in the Channel cable $= 3{\cdot}2$.

LENGTH OF COPPER WIRE LOOPS CORRESPONDING TO CENTIBETAS.

Centibetas.	10.	20.	30.	40.	50.	60.	70.	80.	90.	100.	110.	120.	130.
	Miles	Miles	Miles	Miles	Miles	Miles	Miles	Miles	Miles	Miles	Miles	Miles	Miles
200-lbs. wire	14	28	43	57	71	86	100	114	129	142	157	171	186
300-lbs. wire	20	40	61	81	101	121	141	162	182	202	222	243	263
400-lbs. wire	25	51	77	102	128	153	179	204	230	255	281	306	332
600-lbs. wire	36	72	108	144	180	216	252	288	324	360	396	431	467
800-lbs. wire	44	88	132	177	221	265	309	353	397	441	485	530	574
Centibetas.	140.	150.	160.	170.	180.	190.	200.	210.	220.	230.	240.	250.	260.
	Miles	Miles	Miles	Miles	Miles	Miles	Miles	Miles	Miles	Miles	Miles	Miles	Miles
200-lbs. wire	200	214	228	243	257	271	285	300	314	328	343	357	371
300-lbs. wire	283	303	324	344	364	384	404	425	445	465	485	506	526
400-lbs. wire	358	383	409	434	460	485	511	536	562	588	613	639	664
600-lbs. wire	503	540	575	611	647	683	719	755	791	827	863	899	935
800-lbs. wire	618	662	706	750	794	839	883	927	971	1,010	1,060	1,100	1,150

1 knot of cable (Anglo-French loaded) = 1·67 centibetas.
1 statute mile (Anglo-French loaded) = 1·44 "
484 centibetas = limit of commercial speech.
Exchanges and subscribers = 216 centibetas.

Example.—With 100 miles of Anglo-French loaded cable, how many miles of 600-lb. trunk wire can be worked through?

$$100 \times 1{\cdot}44 = 144. \quad 484 - 216 = 268.$$
$$268 - 144 = 124 = 445 \text{ miles of 600-lb. wire.}$$

APPENDIX XI.

SPECIFICATION FOR ANGLO-FRENCH SUBMARINE TELEPHONE CABLE.

1. *Conductors.*—The conductor of each coil shall be of an approved stranded type, shall weigh not less than 160 lbs. per knot, and shall at a temperature of 75° F. have a resistance not higher than 7·452 standard ohms per knot for a conductor of this gauge. The lay of the stranded conductor shall be left-handed.

2. *Insulator or Dielectric.*—The conductor of each coil shall be insulated by being covered with three alternate layers of Chatterton's compound and gutta percha, beginning with a layer of the said compound, and no more compound shall be used than may be necessary to secure adhesion between the conductor and the layers of gutta percha. The dielectric on the conductor of each coil shall weigh not less than 300 lbs. per knot, making the total weight of the conductor of each coil when covered with the dielectric not less than 460 lbs. per knot.

3. *Inductive Capacity.*—The inductive capacity of each coil of such insulated conductor (hereinafter called the core) shall not exceed 0·275 microfarad per knot, and this shall apply equally to the completed cable.

4. *Insertion of Loading Coils.*—The loading coils will be inserted so that diagonal cores in the cable will be used to form a loop or pair. Each pair of cores to be fitted with loading coils equally spaced at such distances apart and of such inductance and effective resistance as will make :—

(*a*) The volume of speech transmitted over a pair of wires in the completed and laid cable at least equal to that through one-seventh of the same length of standard cable not including terminal losses.*

(*b* The quality of speech or articulation not inferior to that of the speech throughout the standard cable equivalent† of the loaded cable pair.

5. *Interference.*—The two loaded cable pairs to be free from telephonic induction or interference, the one from the other, and also from external disturbance from a contiguous cable.

6. *Labelling.*—Each coil of core before being placed in the temperature tank for testing shall be carefully labelled with the exact length of conductor and the exact weight of copper and dielectric respectively which it contains.

7. *Insulation Resistance.*—The insulation resistance of each coil of core, after such coil shall have been kept in water maintained at a

* Standard cable is that having a wire-to-wire capacity for each pair of wires of 0·054 microfarad per statute mile, a loop resistance of 88 ohms per statute mile, and an average insulation resistance of not less than 200 megohms per statute mile wire-to-wire.

† By the standard cable equivalent of any loop is meant the number of statute miles of loop in a standard cable through which the same volume of speech is obtained as through the loop under test.

temperature of 75° F. for not less than 24 consecutive hours immediately preceding the test, shall be not less than 400 nor more than 2,000 megohms per knot, when tested at that actual temperature, and after electrification during one minute. The electrification between the first and the second minutes to be not less than 3 nor more than 8 per cent., and to progress steadily. The insulation to be taken not less than 14 days after manufacture.

Each coil of core may be subjected, before the ordinary insulation test is taken, to an alternating electromotive force of 5,000 volts and 100 complete periods per second for 15 minutes.

8. *Preservation.*—The core shall during the process of manufacture be carefully protected from sun and heat, and shall not be allowed to remain out of water.

9. *Joints.*—All joints shall be made by experienced workmen, and the contractor shall give timely notice to the Engineer-in-Chief or other authorised officer of the Postmaster-General whenever a joint is about to be made, in order that he may test the same. The contractor shall allow time for a thorough testing of each and every joint in the insulated trough by accumulation, and the leakage from any joint during one minute shall be not more than double that from an equal length of the perfect core.

10. *Taping and Serving.*—The cores to be four in number, and to be stranded with a left-handed lay, and during the process of stranding be wormed with best wet fully tanned jute yarn, so that the whole may be as nearly as possible of a cylindrical form, and shall then be covered (1) with cut cotton tape prepared with ozokerit compound; (2) with pliable brass tape 0·004 in. in thickness and 1 in. in width; and (3) with another serving of cotton tape, similar to the first; the lap in each case being not less than 0·250 in.

The cores, prepared as above specified, shall then be served with best wet fully tanned jute yarn, sufficient to receive the sheathing, hereafter specified, and no loose threads shall, in the process of sheathing, be run through the closing machine. The cores so served shall be kept in tanned water at ordinary temperature, and shall not be allowed to remain out of water except so far as may be necessary to feed the closing machine.

11. *Sheathing.*—The served core to be sheathed with 16 galvanised iron wires, each wire having a diameter of 280 mils, or within 3 per cent. thereof above or below the same. The breaking weight of each wire to be not less than 3,500 lbs., with a minimum of ten twists in 6 in. The length of lay to be 18 in., and to be left-handed.

The wire to be of homogeneous iron, well and smoothly galvanised with zinc spelter. The galvanising will be tested by taking samples from any coil or coils, and plunging them into a saturated solution of sulphate of copper at 60° F., and allowing them to remain in the solution for one minute, when they will be withdrawn and wiped clean. The galvanising shall admit of this process being four times performed with each sample without there being, as there would be if the coating

of zinc were too thin, any sign of a reddish deposit of metallic copper on the wire. If, after the examination of any particular quantity of iron wire, 10 per cent. of such wire does not meet all or any of the foregoing requirements, the whole of such quantity shall be rejected, and no such quantity or any part thereof shall on any account be presented for examination and testing, and this stipulation shall be deemed to be and shall be treated as an essential condition of the contract. Before being used for the sheathing of the cable, the wire shall be heated in a kiln or oven, just sufficiently to drive off all moisture, and whilst warm shall be dipped into pure hot gas-tar (freed from naptha). The iron wire so dipped shall not be used for sheathing the cable until the coating of gas-tar is thoroughly set. No weld or braze in any one wire of the sheath shall be within 6 ft. of a weld or braze in any other wire. All welds or brazes made during the manufacture of the cable shall be re-galvanised and re-tarred.

12. *Compound and Serving.*—The sheathed cores shall be covered with two coatings of compound, and two servings of 3-ply jute yarn the said compound being placed between the two servings and over the outer serving of yarn aforesaid ; the two servings of yarn to be laid on in directions contrary to each other.

The compound referred to in this paragraph shall consist of pitch 85 per cent., bitumen 12½ per cent., and resin oil 2½ per cent., and the yarn referred to shall be spun from the best quality of jute, and shall be saturated with gas-tar freed from acid and ammonia, the yarn being thoroughly dried after saturation and before being used, so as to have no superfluous tar adhering.

13. *Measurement and Marks.*—A correct indicator shall be attached to the closing machine, and a mark to be approved by the Engineer-in-Chief shall be made on the cable at the termination of each knot of completed cable, and also over each joint, or set of joints.

14. *Laying.*—If the tender for laying be accepted, the contractors shall provide the necessary cable-laying ship and all appliances and all apparatus in connection therewith for the laying and testing of the cable during the laying operations. Facilities must be provided for inspection of the work, if considered necessary, by an officer of the Postmaster-General during the progress of the laying operations.

The cable to be laid over the course shown by the dotted red line on the accompanying Admiralty Chart, or as hereafter agreed upon.

On completion of the laying operations the spare cable left on board is to be delivered at the Post Office Cable Depôt, Dover, or paid out and buoyed in the sea near Dover as may be directed by the Engineer-in-Chief.

15. The contractors are required to guarantee that the completed cable shall reach and maintain the standard laid down in the specification, and before final acceptance the cable shall be subject to such tests and experiments as the Postmaster-General may deem necessary during the manufacture, laying, and for a period of 30 consecutive days from the completion of the latter.

APPENDIX XII.

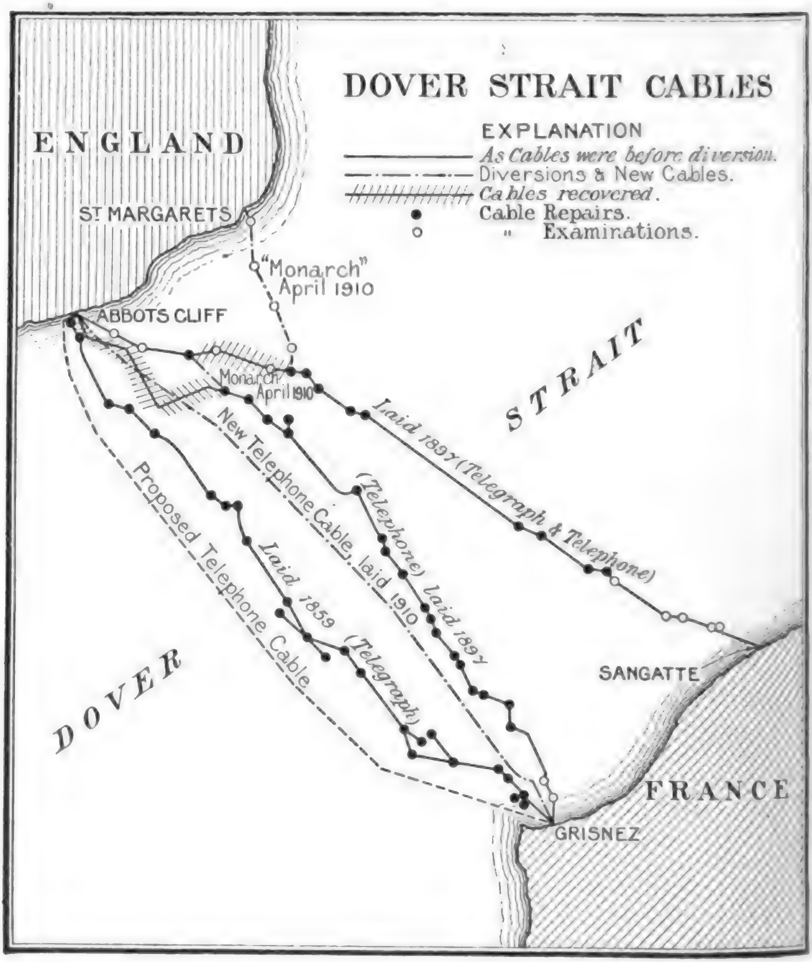


FIG. 17.

APPENDIX XIII.

Tests by Mr. L. B. Turner on the Loaded Channel Cable, to determine by Direct Measurement the Sent and Received Currents.

The experiments were made in the Abbot's Cliff Cable Hut on October 14, 1910.

The high-frequency current used in the tests was supplied from the General Post Office, London, over a pair of telephone wires.

The arrangement of the apparatus was thus :—

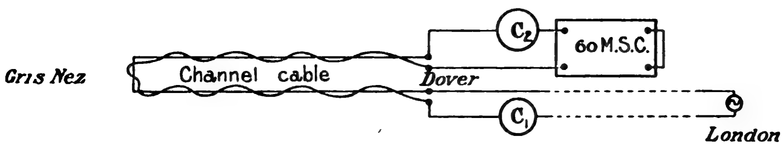


Fig. 18.

To prevent appreciable reflection-effect at the far end of the circuit it was found that rather more than 20-m. standard cable must be inserted. Actually 60-m. standard cable was used.

The ammeters C_1 and C_2 were Duddell thermo-instruments. Their heaters had resistances of roughly 170 and 4 ohms respectively.

There was some difficulty in obtaining a uniform supply from the alternator, and consequently accurate measurements could not be made. The table below includes the only results on which, owing to the unsteadiness of the supply of high-frequency current, any reliance can be placed.

Frequency p.p.s. Readings.	Frequency p.p.s. Mean.	C_1 Milli-amperes.	C_2 Milli-amperes.	$\therefore e^{\beta l}$ ($= C_1/C_2$).	$\therefore \beta l$.	$\therefore$ Me βl.
1,720	—	8·92	2·23	4·00	1·390	
—		6·42	1·80	3·56	1·270	1·33
1,232	—	7·97	3·09	2·57	0·940	
—		8·98	3·38	2·65	0·970	0·96
1,060		6·20	2·54	2·39	0·870	0·87
762	—	7·83	4·28	1·83	0·605	
—		7·02	3·91	1·80	0·590	0·60
744		5·76	3·09	1.85	0·615	
752		4·06	2·33	1·72	0·540	
772	756	5·76	3 09	1·84	0·610	0·59

The following graph is plotted between the mean values for frequency and for $\beta\, l$.

l, the length of loop under test was 40·0 knots.

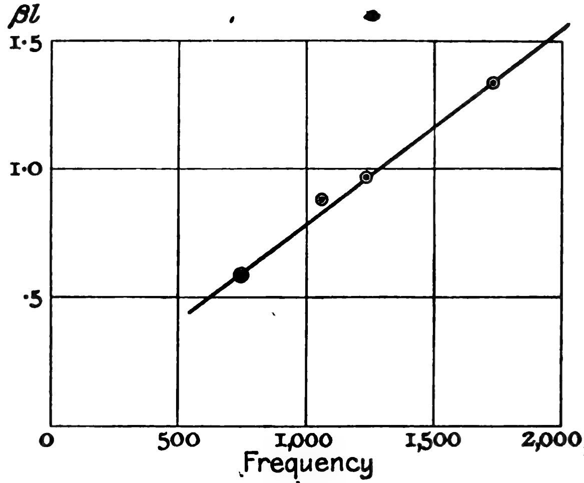


FIG. 19.

To compare these results with the value of β as indirectly obtained by speech tests we proceed thus. That single frequency which best represents the voice, so far as volume of sound is concerned, has been found to be about 800 p.p.s.*

From the graph, for this frequency—

$$\beta\, l = 0{\cdot}63.$$
$$i.e., \quad \beta = 0{\cdot}0158.$$

Assuming 800 p.p.s. to be the simple equivalent voice frequency, the value of the attenuation constant as found by speech test comparisons with standard cable is—

$$\beta = 0{\cdot}0169.$$

DISCUSSION.

Dr. Fleming.

Dr. J. A. FLEMING: It is most interesting to see that the suggestions originally made by Oliver Heaviside more than twenty years ago are beginning to bear fruit in practice, probably not so quickly as could have been desired, but then theorists perhaps have not always recognised that practical engineers who are responsible for the expenditure of large sums of money, as in this case, must advance slowly and make sure of the ground beneath their feet. Nevertheless we have now

* F. Breisig, *Berichte der Deutsche Physikalische Gesellschaft*, Heft 5, 1910.

Dr. Fleming.

arrived at a condition in which these suggestions have been put into practical application. Those who are acquainted with the literature of this subject will, I think, feel that a very great share of the credit must also be given to Professor Pupin, whose papers in 1899 and 1900 * form an era in the history of this subject; because it was Pupin who first gave a practical rule for the spacing out of loading coils. It was quite one thing to say, "Add inductance to cables to neutralise capacity," but it is quite another thing to give practical engineers rules which can be followed in actual engineering for doing it. Pupin's law is very seldom stated; I have hardly ever seen it precisely stated in papers or books on the subject. But it is very simple. He shows that if there be a loaded cable with lumped inductance at intervals, and if you imagine that inductance with resistance and the inductance spread out uniformly so as to make a uniform cable, then the difference between the loaded cable and the uniform cable can be expressed in a very simple manner. If we have a loaded cable with the lumps of inductance at intervals, and we put upon that cable a wave of potential which occupies a certain distance, and we call that wave-length 2π, then the interval between the loads can be expressed by an angle, called θ. Pupin shows that the difference between the loaded cable and corresponding uniform cable of equal total resistance and inductance will be just the difference there is between $\sin \frac{1}{2}\theta$ and $\frac{1}{2}\theta$. This Anglo-French cable practically complies with that law. Take, for instance, the case of a wave-length as in this cable for the frequency given in the paper, 750; I find that wave-length is about 12 knots. So, therefore, if the spacing is 1 knot, the interval between the inductance is $\frac{1}{12}$ part of 360, which is 30°, and therefore the loaded cable is to the uniformly loaded cable as sin 15° is to 15°. The difference between those two is not much more than 1 per cent. So that in that case the cable follows Pupin's law. Morever, it has been shown that the same law is followed for a type of cable which was originally suggested by Professor Silvanus Thompson. On pages 320 and 324 of the paper there are some very interesting remarks on the effect of the leakage on a loaded cable. A doubt appears to have arisen, as expressed on page 320, whether a gutta percha cable could be loaded effectively. It seems to have been suggested that owing to the large dielectric current there may be some difficulty in doing this. I should like to ask the author whether this so-called large dielectric current is a true conduction current, whether it arises from moisture of the gutta percha or any other cause. I find that the attenuation constant of a loaded cable, or in fact any loaded cable in which the pL is large compared with the R, and the pK is large compared with the S, can be quite simply expressed by $\sqrt{\frac{RS}{2}}$ or by $\sqrt{\frac{RK}{2}}\sqrt{\frac{S}{K}}$. This shows why the increase of the S increases the attenuation constant, if that S in this case is really a true conduction current. Then there are

* *Transactions of the American Institute of Electrical Engineers*, vol. 19, p. 93, 1899; vol. 17, p. 445, 1900.

Dr. Fleming.

some very interesting statements in the paper concerning the uniformly loaded cable and the difficulties of pre-determining the attenuation constant of uniformly loaded cables. I venture to think this difficulty arises from the difficulty of pre-determining the permeability of the iron for small high-frequency magnetising forces. I have recently been carrying out some experiments in my laboratory on that very point, and I find that a very simple and effective way of determining the permeability for low forces of iron wire is to measure the high-frequency resistance of the wire in a way I described some few months ago at this Institution in a paper on "Some Quantitative Measurements in Connection with Radio-telegraphy." * In that way we can find the permeability for small forces, such as those we are concerned with in telephone currents. I find that the magnetic permeability of the iron for these low forces is very much lower than would be imagined from the ordinary magnetisation curves. Therefore if we work from the figures of the ordinary magnetisation curves we assume the permeability to be much larger than it really is, and therefore the attenuation will come out less than it is in actual practice. This may prove to be a means for the determination of the permeability of uniformly loaded cables. Without doubt the author has provided us with the means of comparing theory and practice, and correcting the theory where it happens to be faulty.

Mr. Dieselhorst.

Mr. W. DIESELHORST: Some remarks made at the Conference of Government Telegraph and Telephone Engineers in Paris seem to have left the impression on those present, as well as those who have read the published proceedings, that difficulties are anticipated in repairing submarine loaded cables. Since Messrs. Siemens Bros. & Co., Ltd., are responsible for the entire construction of the loaded telephone cable recently laid across the Channel, with the exception of the dimensions of the core and the sheathing, and have, in their opinion, taken every care that no such difficulties should arise, I should like to ask the author why, and on what grounds, such difficulties are anticipated. Knowing the behaviour of the cable in question during laying and during picking up of one of the coils, I have no reason to suppose that any difficulties need arise during a repair. I may also mention that when the amount of self-induction to be introduced and its spacing was determined by those responsible for its design, the distribution of the necessary self-induction was so chosen that it allowed of a large displacement of one or several coils during necessary repairs. This is in agreement with the author's remarks on the point.

Sir John Gavey.

Sir JOHN GAVEY: I should like to congratulate the author on the bold and successful manner in which he has tackled this very serious problem of increasing the carrying capacity of our telephone submarine cables. Through the old cables that were originally laid across the Straits of Dover the limit of speech from London, if my recollection is right, was reached at Lyons on the east and Marseilles on the west.

* *Journal of the Institution of Electrical Engineers*, vol. 44, p. 344, 1910.

Sir John Gavey.

How the author has extended that distance he has already told us. Much of this improvement is, of course, due to the increased efficiency of the loading coils. I remember some years ago, when we commenced experimenting with loading coils, we found that the effect of iron in the core was, it is true, to increase the volume of sound, but also to impair the articulation, and the result was that for some years the Post Office devoted its attention to developing loading coils without magnetic cores. There were several objections in practice to the use of these coils, but as they do not affect the question of submarine telegraphy, I will not waste time by referring to them. But in the course of time the improvements made in loading coils with magnetic cores has been so great that it will be observed that they have increased the carrying capacity of this type of cable 3·5 times, as compared with about two and a half times the maximum possible a few years ago. The subject of continuous loading has attracted my attention for some time past, because I think there is room for the use of this method in connection with the land lines necessary to connect submarine cables with the great centres of commerce. In the past the Post Office has erected very costly trunk lines. The weight of copper to the mile has been adversely criticised in some quarters as being extravagant, but even with the so-called extravagant weight of copper per mile, the conductivity has been reduced by the entry of rival electrical enterprises into the field. The spread of electrical tramways with overhead trolley conductors all through the country has led to the need for leading these heavy gauge wires into post offices in most of the towns they traverse, and fitting them with heat coils and fuses, with the result that generally the effective conductivity of our heavy conductors has been reduced by nearly 20 per cent. through the addition of these protective devices. Again, the Post Office has done what it could to maintain overhead wires for trunk-line purposes in all the large centres of commerce, but the difficulty of doing so becomes greater day by day, and the time will arrive when most, if not the larger portion, of these town sections will have to go underground. It occurred to me, in connection with a similar problem I had to deal with in Buenos Aires, that we might with advantage introduce continuous loading, if not on submarine cables, on underground work. It appeared to me that in the first efforts to deal with that question of continuous-current loading possibly some mistakes had been made. The superimposing on the copper conductor of two or three layers of a very fine wire in order to get the necessary magnetic field meant a great deal of cost, considerable waste of space with increased electrostatic capacity, and, further, the iron wire was hardened in lapping it on the conductor; and this, no doubt, was one of the factors which prevented the application of the ordinary formula in determining the value of β. I therefore prepared a specification for an air-spaced insulated cable, the conductor to consist of a 100-lb. copper wire, lapped with a very soft iron tape, $\frac{1}{100}$ in. in thickness and $\frac{1}{16}$ in. wide, the compound conductor to be

Sir John Gavey.

thoroughly annealed, then coated with a hard varnish and insulated with paper in the usual way. The contract was taken by the British Insulation and Helsby Cables Company; a great deal of time was spent on the preliminary experiments, and the result obtained on the first sections that were tested was that we got a conductor with a self-induction of L = 10 milliamperes per mile as compared with 1 milliampere in the unloaded cable. The effective resistance was 20·2 ohms per mile loop, and the calculated value of β was 0·024. This indicated an improvement of 70 per cent. on the ordinary unloaded cable. The speaking tests similar to those described by Major O'Meara gave 4·34 miles of the loaded cable as equivalent to 1 mile of standard, an improvement of 77 per cent., so that the calculated and the observed results were very close. We obtained a further improvement a little later as the result of extended experience in manufacture, and in the second lot of cable the tests gave a capacity of 0·059 microfarad, a self-induction of 17 millihenries, and an effective resistance of the loaded conductor of 22·4 ohms per mile at a frequency of 800; the value of β was reduced to 0·0207, and 4·97 miles of this cable were equivalent to 1 mile of standard cable. This gave a calculated improvement of 103 per cent., as compared with 100 per cent. by speech test, and the speaking tests on the whole cable gave an improvement of 94 per cent. From those results I deduced the fact that, given a knowledge of the magnetic properties of the lapping of iron, and taking care that if it is hardened, as it must be in winding it on a small conductor, it is subsequently annealed, then the ordinary formula given by Pupin will make it possible to determine in advance what the improvement is in the cable. I notice, too, that the value of the induction L is very close to that calculated and shown in one of the tables prepared by the author. At all events, we can say that, although the original submarine cables continuously loaded only gave an improvement of 60 per cent. in their transmitting power, we have already by adopting improved measures obtained an improvement of 100 per cent.

Mr. Kempe.

Mr. H. R. KEMPE: Major O'Meara has been kind enough to refer to the part which I have taken in the question of submarine telephone cables. My investigations have not been so much in the domain of theory, but more in the direction of simplifying theory if possible, and what is more important still, in getting practical data in order to enable theory to be brought into practical operation. Some few years ago I was interviewed by a newspaper correspondent, and I recollect showing him one of the coils which we used for our underground loading. It was of a somewhat large size, and what I said to him was this: "Is it possible to put a block like this into a submarine cable? It is practically impossible." My opinion on that point, on the possibility of loading by such means, has been very considerably modified since then. Later on, Mr. Dieselhorst was good enough to show me what he had done in the direction of placing loading coils in submarine cables, and I expressed a certain amount of

doubt as to their utility even when I saw what he had done. I must confess I was by no means confident about them, but I felt that a movement had been made in the right direction, and that the whole problem of loading submarine cables was near, if not very close indeed, to practical realisation. The experimental coil which he made at that time is practically the arrangement which has been adopted in the present Paris cable. Mr. Dieselhorst asked whether Major O'Meara could give some information in reference to the question of repairing the type of cable in which he was so largely interested. I have no doubt he will be able to do so, but I should like to add my quota of information, not so much in regard to the repair of the cable, as in regard to its durability. Certain wiseacres have shaken their heads and made the remark, "Yes, the cable is down, but will it last?" A remark of that sort is nearly always made in connection with every new enterprise; when the first Atlantic cable was put down it was queried, "Will it last?" I may say that I have had the new cable under my observation ever since its birth. I made tests on it the moment after it was laid, and I also made a series of tests from month to month for a considerable period, and I can testify that the condition of the cable when I last tested it was exactly that of an ordinary cable which had not any loading coils in it; in other words, the cable is just as perfect as any ordinary submarine cable, and there is not the slightest doubt in my mind that the cable will last as long as any form of cable which has yet been put down. Even if the cable had failed, my faith in it would not have disappeared. If a failure had taken place the cable would have been picked up and the cause of the failure would have been found, and that failure would have been remedied. The question of "leakance" is of very great importance, and we have much to learn on that subject. An experiment was made not very long ago on a condenser by one of my personal staff. He took a one-third microfarad condenser, the normal insulation resistance of which was many thousand megohms. Under a current of high frequency —I think 1,000 or 2,000—the insulation went down to 8,000 ohms, which shows the extraordinary results obtained from high-frequency currents. There is another curious point which Mr. Dieselhorst has drawn attention to, namely, that we may have two dielectrics of different qualities, one dielectric having a high resistance under a steady current and the other dielectric a rather lower one; then the one that is highest with the continuous current may become the lowest with a high-frequency current. What the cause of that is is not known at present, but I mention it as a curious fact upon which possibly some one may be able to throw light. Some difference of opinion appears to exist as to whether coil loading or continuous loading is best. The whole question, in my opinion, is purely one of finance. A low value of β can be obtained without any loading at all, by making the conductor large enough and the dielectric thick enough, but that will produce drumminess, which can only be got rid of by loading with a certain amount of inductance. I believe the best Mr. Kempe.

Mr. Kempe. result obtained at present by continuous loading is an improvement of about 70 per cent.; possibly by further investigation it may be practicable to obtain a higher percentage than that; but with the new Channel cable an improvement of 220 per cent. has been obtained. If we worked out the actual cost we should probably find that the low value of β obtained by means of loading coils is less than that obtained by continuous loading. There is another point to which I wish to refer in connection with continuous loading. If we have a set of underground wires, the cable containing perhaps 100 wires, and they are not all required for telephone purposes, then only half a dozen of them may perhaps be loaded, but later on it may be found that twenty are required. What is to be done then? We cannot draw out the wires, continuously load them, and then draw them in again, but, on the other hand, we can load them by means of coils, and from that point of view, therefore, apart from the question of cheapness, it is quite possible that loading by means of coils may in many cases be preferable, although the space which the coils take up is a somewhat serious item; any experimental evidence which will enable the size of the coils to be materially reduced will be of very great value. Referring once more to the question of continuous loading, I may mention that the Post Office is at present engaged in making an extensive series of experiments in order to determine the permeability of iron and the conditions under which we can obtain continuous loading in the most simple and most economical manner. "Drumminess" has been referred to. What constitutes "drumminess" is very much a matter of individual opinion. When the first telephone cable was laid down across the Channel, it was not loaded, but yet it was considered to be a great success, and I think the public were entirely satisfied with the quality of the speech they obtained—certainly it was not considered to be "drummy." But when they come to speak through the loaded cable there is no doubt they will say, "This is very much better." They do not say that the cable which is not loaded is useless, they say it is "drummy" compared with the other; hence the necessity for a standard of articulation clearness. I want to mention one fact in connection with Appendix VIII. in regard to the investigations which I have made. My aim has been, as I pointed out when I commenced my remarks, to obtain as far as possible simplification in the formulæ. Now we have a most alarming formula in that appendix, with reference to the inductance obtained by means of continuous loading. The real reason why that formula is left in its present form is the absence of knowledge of the value of the various constants. When once data are obtained which will enable one to determine the actual value of certain constants, the field of the particular equation concerned becomes considerably narrowed, and we are brought down to practical limits; and under those conditions the equation can be much simplified. With a long formula one is liable, when giving the various elements their numerical values, to make mistakes which may only be discovered when the calculation is complete, and then all the work has to be gone through again, and that operation may have to be repeated several times.

Mr. A. WHALLEY: Referring to Fig. 4, may I ask how the joint is made strong enough to be pulled through the standing machine before it is armoured? Apparently a new cable is to be laid by the French Government in its turn. May I ask also if it is yet known when that cable will be laid, and of what type it will be? Presumably the introduction of loading coils with relatively thin insulation on the two wires will demand special protection against lightning. The chief point, however, that I wish to raise is the value of β as it appears in the paper. We find five different values given for the new cable as the result of tests. The highest and lowest appear to be the speech values, and they differ by 14 per cent., both having apparently been made by comparison with an artificial standard cable, perhaps with the same standard cable in both cases. If the lower figure be correct, then apparently the average frequency of the British male voice is rather below 750 instead of above. Possibly this artificial standard cable has a higher β value than is indicated, and this has caused the results to appear rather low in any cable measured by comparison with it. Three of the figures for β are measured by means of an alternator, and they agree fairly well together. Two of them are recorded, and one of them can be deduced from Fig. 19. May I ask why 1·66 centibetas is adopted for this cable, if the average of the other four tests is nearer the figure 1·5? An excellent curve is given on the last page (Fig. 19) showing how the value of β for this cable varies with frequency. We have three frequencies given in the paper: 750, 800, and 900. At 900 by this curve β is 20 per cent. higher than at 750, and at 800 it is more than 5 per cent. higher. Though this curve is excellent, it would be still more so, and fill one more of the blank pages of our records if the author would be so kind as to add two more curves to it, one to show the old Anglo-French cable and the other to show a typical air-space land cable. Dealing also with β in Appendix VIA, page 338, a column is given in which they are not all apparently on the same basis. Some are speech tests; some have a frequency of 900, and one or two may have been taken at 750. It appears therefore to be important when declaring the values of β to make it clear how far frequency affects them, and whether terminal losses are included or allowed for when β applies to a loaded cable. Speech tests, according to the four gentlemen who went to Dover for the purpose of measuring the "gain" by loading compared with the old cable, give results varying from 14 to 26 miles, a difference of nearly 100 per cent. This is one of the best illustrations we can have of the unreliability of speech tests for determining cable constants. It is to be hoped that the alternator method with reliable frequency control* may be developed to produce a composite wave representing a fairly average speech wave by the use of several machines. One interesting point arises with regard to tests made by these four gentlemen. Each worked out his own limit of audibility. They naturally varied amongst themselves, but I should like to ask if the lengths in standard miles of each of the

Mr. Whalley.

* *Post Office Electrical Engineers' Journal*, vol. 3, p. 10, 1910.

Mr. Whalley.

two cable circuits have been worked out, and do they agree? As regards the continuously loaded cables, the particulars given about one of them—the Danish-Seeland-Zutland—do not appear to be in agreement, as on page 340 the figures are nearly half of those given on the other pages, and it looks as though either β applies only to the single conductor of the loop instead of two conductors, or else as though possibly by an error the figure applies to a loop kilometre instead of to a loop knot. The difference is 1·56 centibetas, page 340, against 2·96, pages 338 and 345. From Fig. 2 we are able to deduce the terminal loss on one of these Danish continuously loaded cables. On a 20-knot cable it apparently has the effect of increasing the length by 16 per cent. Is there not an error in the horizontal line of Fig. 2? Should it not be either "βl" alone or else "miles of equivalent standard cable"? I can find in the paper no indication of the true terminal loss of the Anglo-French loaded cable. Apparently this loaded cable is five times better than standard cable, which means that a working length of 20 knots is equal to 4 knots of standard, and of these 4 knots 1·2 represent the terminal loss, leaving 2·8 to represent the cable. But then 1·2 knots of standard cable is equivalent to 8·7 of the real cable, this meaning the addition of 8·7 knots to a length of 20 knots, or apparently 43½ per cent., to represent the terminal loss at the ends due to reflection if such loss cannot be neutralised. This figure agrees fairly with the results given by Mr. Martin, in his paper before the Post Office Institution, for air-spaced loaded cables, in which the terminal losses varied from 40 to 65 per cent., whereas in the continuously loaded Danish cable the terminal loss appeared to be 16 per cent., all for 20-knot lengths. Why should we not have a "Kempe"? As regards the new term "centibeta," I am afraid it will be confused with "centimetre" in conversation. With regard to the term "improvance," we must be on our guard to indicate whether it includes terminal loss, and for what particular length of cable that loss is included.

Mr. Siemens.

Mr. Alexander Siemens: With regard to the diagram which shows the telephone cables across the Channel and the number of repairs which have been made, nothing has been said as to what was the cause of the faults. I should be very sorry indeed if the audience thought that the cables had been so badly manufactured that they had to be repaired for that reason. I want to make it quite clear that the fishermen's anchors are responsible for the repairs, and not the badness of manufacture of the cables. Then, if I may find another fault, I notice the author has spoken of a length of cable of so many "knots." Now, that hurts a sailor's feelings, because a "knot" is a rate—viz., 1 nautical mile per hour. The correct term is "nauts."

Dr. Silvanus Thompson.

Dr. Silvanus P. Thompson: It is clear that mathematical calculations land us in a difficulty, because one does not precisely know to what to apply the calculations. It is all very well to take a frequency of 750 and see what happens on applying mathematical calculations. It means that we are working only for this one particular note. We

Dr. Silvanus Thompson.

do not always speak on that particular note. We speak in various notes, bass and shrill; the very vowels we use are of different frequency, and are compounded of different frequencies, and any mathematical solution we obtain on the assumption of one frequency will be wrong for any other. That is to say, if we had a cable that was absolutely and perfectly compensated for one particular note, then when we talked through the cable that note, if we hit upon it, would sound out louder than anything else or than any of the other elements of the compound. "Drumminess" consists in the prevalence of a booming note among the general periods of speech, so that evidently we can only get at an average result at the best; and it is evident that experiment will have to play a very great part rather than pure theory in determining what ought to be done. The difficulty of continuous loading has been referred to, and I was exceedingly glad to hear from Sir John Gavey of those further improvements which have been made which apparently render continuous loading quite as practicable as any other. It has been pointed out that there is an apparent increase of resistance due to the reactions that occur in the performance of inductive coils, and it has been suggested that this is an objection to the use of the inductive coils. I venture to point out that that is only the case if they are placed in series in the circuit. But if inductive coils be used in the manner I proposed in 1891 as shunts at intervals across the cables, then the increase of resistance will certainly be of no harm, and possibly may be of some benefit.

That leads me to put in a word on behalf of the particular variety of compensation that I put forward so long ago, and which has not yet received the same grateful attention from His Majesty's Government, nor indeed from other authorities, as has the rival method of putting in inductance coils in series. Professor Fleming was good enough to point out that the mathematical theory is the same for both so far as distribution is concerned, but the problem is really a very different one. I did not arrive at the suggestion I made from anything that I read in Heaviside; that would have led me in another direction. In 1874 G. K. Winter* described the use of inductive resistances in cable signalling, such shunts being used at the ends of the cables, as Varley had previously used them. If an inductive shunt placed across the ends of a cable will improve its action, why will not inductive shunts when placed anywhere else? I proposed to put inductive shunts along at intervals as leaks from the cable to the sheathing, or between two separate cores—inductive leaks which would accelerate the speed of telegraphic signalling, and might be hoped to do the same thing for telephoning. I was led to believe it would be good for the telephone because of a communication to the British Association † made by Sir (then Mr.) William Preece in 1891, when the London-Paris telephone line was constructed; for it was found that the talking between London and Paris was in no way

* *Journal of the Society of Telegraph Engineers*, vol. 3, p. 103, 1874.
† *Electrical Review*, vol. 29, p. 247, 1891.

Dr. Silvanus Thompson.

interfered with when telephonic receivers were bridged across the circuit at the two ends of the cable; in fact, such bridging rather improved the working of the line. I said, Why not bridge elsewhere than at the ends? If the evil is distributed all along, how can we fight it by things put at the ends? Fight that distributed evil by a distributed remedy. Put bridges at such intervals as may be necessary. Since then we all know what a great advance has been made in the speed of submarine signalling by Mr. Brown, by the identical means of putting an inductive shunt across the cable to earth at the ends, exactly what Varley and Winter proposed, and what I mentioned in 1891 as the starting-point of my ideas. I proposed to do the same thing at intervals all along. I suggested that for telegraphic signalling one might be required every 500 miles, or possibly every 100 miles, and for telephonic signalling it might be every 10 or 20 miles. From to-night's discussion I judge that 12 nauts appears to be the proper thing for telephonic signalling. To make an Atlantic cable that will telegraph easily 300 words a minute, we shall require one such inductive shunt across every 360 nauts; which, on an Atlantic cable 2,000 miles long, will mean five such shunts only 360 nautical miles apart; and with an additional one at each end you will have altogether seven inductive shunts across as bridges. If you want to signal 1,000 words a minute you must place a shunt every 110 nautical miles, which would mean having 18 shunts as bridges across, acting as inductive leaks. Is there any trouble in testing them? We have heard there is nowadays no trouble in testing things that have induction in them. Is there any trouble in repairing them? We are told not. Is there any trouble in laying them? Even there we are told there is not. Then I plead once more for my particular solution, that it should be given a trial exactly as fairly and as squarely as that given to the other method.

Discussion at Meeting of January 12, 1911.

Right Hon. Herbert Samuel.

The Right Hon. Herbert Samuel, M.P. (Postmaster-General): Mr. Chairman and gentlemen, unfortunately I was unable to hear the paper that was read at the previous meeting of this Institution. I was, as some of you may think, better employed, some of you may think worse employed, at the time electioneering in the country, and consequently I speak this evening under some slight disadvantage, though indeed it is not a very great one; for even if I had heard the paper, and even if I had had an opportunity of studying it since, I am afraid that, as a mere layman, I should have been able to say nothing which would have been of value to a gathering of electrical engineers. As you would naturally presume, I am not an expert in the matters with which you are accustomed to deal. Nevertheless I have had some personal experience of the results that are achieved by the particular method which has been adopted by Major O'Meara in the new submarine telephone cable between England and France, for that cable was one afternoon connected with the telephone instrument in my room at the House of Commons, and several of my colleagues and myself were able

Right Hon. Herbert Samuel.

to test by actual experience the difference in the transmission of speech by the old cable and by the new. No one can have that experience, and actually hold the instrument at his ear and at one moment speak to Paris through the old cable and at the next speak to Paris through the new cable, without realising the extraordinary difference in efficiency which has been achieved by the invention that has lately been adopted. Indeed, this new cable opens up very wide vistas of future telephonic communication. It is always assumed that Government Departments are devoid of imagination, that the officers of Government Departments are swathed in red tape, and that the bureaucrat is the most unprogressive of human beings. No one, I think, in these days, can make these accusations against the Post Office, certainly they cannot make such accusations against the Chief Engineer of the Post Office, for his imagination is of a soaring kind, and he promises us at no very distant date, if a somewhat coy Treasury is ready to provide the necessary means, to establish telephonic communication even between London and Calcutta. Whether that date is so near at hand as optimists may suppose is, of course, a matter of opinion, and a question which only experience can solve. But certainly it is the very earnest desire of those responsible for the direction of our postal, telegraphic, and telephonic communications to extend as rapidly as may be the radius over which telephonic communication can be carried, and, as speedily as may be, reduce the charges to the public for the use of those facilities. Already, thanks to the provision of this new cable, and to the additional facilities which it makes possible, we shall be able in the near future to reduce by 50 per cent. the telephonic charges for communication between London and Paris, and in other ways in the future, we trust, that other diminutions of charges may be effected. The Post Office is no longer a mere institution which sells stamps and carries letters; it is already, possibly, the largest electrical business in the country, and is becoming more and more a highly specialised engineering undertaking. As telephony develops, so it will become in increasing degree a field for the operation of the electrical engineer. If only in this country we had the standard of telephonic use—the amount of use made of the telephone which has already been attained in the United States (and to that end we are rapidly working with all the means in our power)—if we had achieved that standard, there would, indeed, be a vast field for the work of electrical engineers under the supervision of the Postmaster-General. With a view to those developments in the present and in the future it is necessary that our Post Office engineers should have the highest electrical qualifications, and various changes are being effected in the internal economy of the Post Office system with a view to securing that a really high standard of efficiency shall be attained by those engineers who are working in the service of the State in that Department. Well, to-night it is, of course, not my task to take part in the technical discussion which is about to begin. I would only say that it is a great pleasure to me to visit this fine and, indeed, palatial building which your Institution has provided for itself.

Right Hon. Herbert Samuel. I should like to take advantage of this occasion to express my acknowledgments, and the acknowledgments of my Department, to your Institution for your kindness in allowing the use of your building to the Society of Post Office Electrical Engineers, who, I know, very greatly appreciate the facilities which you have been good enough to give them. For myself I would only thank you most cordially for the opportunity which you have given me of listening to the discussion to-night.

Mr. Gill. Mr. F. GILL: I think we are very greatly indebted to Major O'Meara for placing at our disposal the results of the Anglo-French cable and also a number of other very valuable results. I think also, if I may say so, Messrs. Siemens are to be congratulated on an exceedingly interesting piece of work very well performed, perhaps none the less interesting because in this case, I understand, the designing, laying, and everything else was left to the manufacturers, who were to produce results.

In reading over the paper I have come across a few difficulties, and if Major O'Meara would have some of these cleared I think it would add to the value of the paper, because I am sure that frequent reference to it will be made as times goes on. In Table A, I think the first line may refer to the cable mentioned in Appendix VII., cable E; the wrapping is the same, but the attenuation constant is different. Is that due to a different frequency? If so, perhaps the author will tell us what it is. Table B refers to an actual coil-loaded cable, but I think the first line is the Anglo-French cable. If so there is a very obvious slip which probably the author has noticed. In the second line he gives the attenuation constant as 0·0766 per naut. That gives an improvement of 4·61 due to coil loading, which at once arouses suspicion. If we then turn to Appendix IXA, where particulars of the Anglo-French cable are given—and where incidentally the attenuation constant per naut is given at the same figure, namely, 0·0766—we get the data from which to calculate the attenuation constant, and we find it is not 0·0766, but 0·0522 per naut, or 0·0453 per mile. That agrees with Mr. Kempe's figure of improvement of 3·2; I think the error misled one or two of the speakers at the last meeting.

On page 329 Major O' Meara says that the gain by the use of the new cable is 17 standard miles on the speech test. But the equivalent length is, I believe, 10·46 standard miles for the unloaded and 3·32 for the loaded, that is a difference of 7·14 standard miles, and as talk was over double the distance the gain would then be 14·28 and not 17 at all. If 17 is right then the attenuation constant is wrong. I think the real point is that 17 is not right, and the attenuation constant is correct.

In Appendix VI., Fig. 14, the weight of copper is the weight per strand, not the total weight. In Appendix IXA, if Major O'Meara would add to the details there given, the total length, the equivalent, and the initial sending end impedance, or characteristic as it is sometimes called, he would help us.

Now coming to the paper itself, on page 320, reference is made

to some coils which were used for certain experiments. I am afraid they were very inefficient coils—one might almost call them "shocking" coils. The resistance for 1 henry was 162 ohms, over 2¾ times as much as for the coils made by Messrs. Siemens. I think that suggests they were air-core coils—I do not know, but it rather suggests it—and if so that illustrates as well as anything the impracticability of getting the desired result with air-core coils. I hope I may now congratulate Major O'Meara on having given up air-core coils, and taken up the use of iron-core coils, which have been available for some years. Mr. Gill.

The author has mentioned Dr. Breisig's experiments. I took part in those experiments; of necessity only a short time could be given to them, and I did not feel at all satisfied, but came away from them in considerable doubt. We know that with dry core-cable and open wire the same βl does give very much the same class of talk, with what may be called a colour difference, and Major O'Meara may remember some experiments made at the end of 1904 in which this was demonstrated. But in Dr. Breisig's experiments for the same βl there was a very great difference in the talk, and that at once raised suspicion as to the build of the artificial cable.

In Appendix X. Mr. Kempe states that a minimum value is given to β if the conductor resistance of the cable per unit length is 0·14 times the millihenries per unit length. I should like to take this opportunity of saying that several years ago Mr. Shepherd gave me an expression for exactly the same thing, and it is only due to him that I should mention it. The figures were a little different; they were 0·127 l instead of 0·14 l. Mr. Shepherd was working with dry-core cables at the time.

Major O'Meara has shown that there is a very poor case for continuously loaded submarine cables; in fact, I think he has shown that, unless there are mechanical difficulties, the continuously loaded submarine cable has not any claim. It seems to me very probable that Messrs. Siemens' arrangements have got over that difficulty. If that is so there should be no more continuously loaded submarine cables. But the case for land lines as usually laid is even worse. In this case the cost of the insulation is not expensive—it is only paper and air; but the cost of the lead sheathing and the duct containing the cable is very expensive, and by continuously loading you increase both those costs. So far as economy is concerned, it is not too much to say that the claim for coil loading is as great on the saving of the cost of the duct space as on the saving in the cable. I know that loading goes beyond economy; it enables you to obtain results you could not get otherwise, but I am not referring to that point. Sir John Gavey gave an illustration at the last meeting, and I have had a case worked out. He did not give the length of the line, but I assumed it was a short line. I therefore took 3 miles of underground cable at the end of a long open trunk line. It was a 100-lb. cable loaded with iron tape, so that the attenuation constant was 0·0207 per mile. You can get equivalent talk if you replace that by a 70-lb. cable loaded with two

Mr. Gill. coils in that distance giving an inductance of 0·09 henry per mile. When we compare the annual costs we find that, taking the continuously loaded cable as 100, the coil-loaded cable is 56. If the cable be placed in the ground with no duct the costs are still very strongly in favour of coil loading. There has been a good deal written on the question of continuously loading heavy conductors, mainly on the Continent, and, as far as I can see, most writers have ignored this question of the cost of the duct space. Mr. Kempe has referred to the very great advantage given by flexibility, so that there is no need to go over that point again. On account of the Post Office owning the long lines in this country the National Company's practice has had to be confined to very short lines. We began this work in 1906, and we have now loaded, or are loading, over 2,500 miles of circuit. Take one example to show what is being done on very short lines; a line 3½ miles long is made up of 20 lb. cable, and by the insertion of two coils the equated length is reduced from 3·5 to 1·9 standard miles, an improvement of 1·84, not necessarily the best that can be done, but sufficient for the purpose in view. We have not up to the present done any loading with one coil only, but experiments and general work indicate that we can put one coil in a short length, and get an improvement of, say, from 1·2 to 2. Dr. Thompson had asked that his method of parallel loading should be given a trial. I think on consideration Dr. Thompson will see that that method is entirely unsuitable for telephone conditions, and I do not think he is at all likely to see his desire carried out.

Then I should like to say a few words about the standard mile. The standard mile, or standard kilometre, is, of course, an arbitrary unit, and doubtless it would be better if it were based on the C.G.S. system; but it satisfies a certain need at present, and is doing useful service, and I very much doubt if we are ready to drop it and to take up the proposed unit. There are very weighty reasons against this proposal. The propagation constant is made up of two parts: the attenuation constant and the wave-length constant. It is true that in ordinary work we ignore for the moment the wave-length constant, because comparisons are made against a standard mile in respect of which the wave-length constant is well known. But this proposal relies on the attenuation constant only and neglects the wave-length constant altogether; before all work can be expressed in terms of attenuation length the instrument or apparatus by which the attenuation length is to be measured must be precisely defined so as to cover the wave-length question. Until that is done I think the suggestion is a partial one and cannot practically be carried out. Further, the readings would be true for one particular frequency only—an arbitrary frequency, shall I say—and would therefore be liable to revision every time the mean frequency of speech is more accurately determined. Again, they would be of no use for telegraphic work, because telegraphic work might not have a frequency corresponding to that of speech. I am no opponent of scientific nomenclature, but I do

not think there is any use in starting to make an alteration unless we are ready for it. Mr. Gill.

The author mentions three methods of increasing the range of transmission; there is a fourth which he does not mention. If you take four wires forming two pairs of circuits and by means of repeating coils make a third circuit, although you get a loss on the two physical circuits, after a certain length has been exceeded you get a gain on the third circuit, the phantom circuit, and that is then better than the two physical circuits were before the coils were introduced. By making certain assumptions as to the land lines I calculate that the old circuit from London to Paris has an equated length of 22·34 and the new 15·18 standard miles. If the old cable circuit were duplexed (I have no experience with gutta percha cables, and therefore I may be all wrong) I would expect there would be a gain of something like 10 standard miles on the whole circuit; that is to say, the duplex circuit would give a result considerably better than that obtained by the new circuit. It is true there would be a loss on the physical circuits; but the question which arises is, Would it be possible to limit the two physical circuits to short-distance traffic and let the phantom circuit take care of the long-distance traffic? Major O'Meara may say that that is already in contemplation. I would like to know whether it is proposed to load the aerial circuit on the new cable, and, of course, I want to know whether the author is going to duplex the old cable circuit and whether the new cable can be successfully duplexed. I know that Mr. Carty has shown lately that it is now possible to gain a further improvement still by loading the phantom, but I do not refer to that because at the time the Anglo-French cable was made it was not feasible to load a phantom circuit.

Mr. D. SINCLAIR: To some of us who are older at the business it is delightful to think that the speaking capability of the cable connecting France and England has been improved by something like three or four times. That is very good news for every one who wishes the industry well. I would like to add to what Mr. Gill has said that I think Messrs. Siemens should be very proud of the part they have taken in the matter. Looking back over a great many years, the position strikes me something like this. There was a day when iron in connection with long lines was anathema. Some of us were foolish enough to have erected iron lines, but we had to take them down and put up copper for which somebody had to pay. With succeeding years the time arrives when we are told that the best circuit is a combination in some shape or form of copper and iron. To the scientist perhaps more than to the practical man, I think, we are indebted for that knowledge. Now the problem before us is how to make the best use of copper in conjunction with iron. That Pupin coils give the best results at present goes without saying, but I do not think it would be a healthy position for every engineer to say that it must remain the best and only method. I think it is the duty, especially of younger engineers, to see if they can get something nearly as good, or better, Mr. Sinclair.

Mr. Sinclair.

in some other way, and I will state my reasons. If we introduce these coil connections every 3 miles in the line, say, between London and Glasgow, to an old telegraph engineer that would seem equivalent to introducing so many test-boxes in the line; and if there was a devil in the circuit at all in the old days it used to be in the test-box. One or two of the test-boxes had, usually speaking, a dry joint, and that dry joint was the cause of endless trouble. I do not know whether the skill of the British workman, or any other workman, under the supervision of excellent engineers has overcome the frailty that attends the cutting up of circuits into such short distances, but it is something that has to be taken great care of, and it is something that, under conditions where supervision is expensive or scarce, or cannot be had at all, might not be admissible. Therefore some engineers have looked at the question with a view to producing the desired result without introducing what I call this enormous number of test-boxes. That is more perhaps an old prejudice than a material fact at the present day. Sir John Gavey approached my company some time ago on this very interesting subject, and asked if we would make a length of continuously loaded cable to try this experiment. We looked into it, and we found that by putting iron strip round the copper conductor we could start off with an improvement of something like 60 per cent., that being the best result previously obtained with continuously loaded cables. We have been conducting experiments for six or seven months, and have produced and delivered a cable that has tested up to 102 per cent. improvement on a length of 47½ miles of loop, and tests on short lengths show that we can do a very great deal better than that, but just how much better we can do I would not like to say at present. The improvement is so serious that I do not think the matter should be left there or taken lightly. I think the experiments should be extended further, and we are therefore making at Prescot another length of cable where the improvement will be much more than 100 per cent. Where you have a long line of open wires interspersed with short lengths of cable, it is difficult to introduce Pupin coils and get a good effect, but it is not difficult to introduce continuously loaded cable of this class. I have an impression myself—I may be wrong—that there are many conditions and places where this cable could be used. The question arises whether you can use it commercially, and Mr. Gill has said that the cost of the pipe requires consideration in that connection. What takes place is this. When you increase the size of the copper conductor by winding iron on it you increase, if you retain the standard capacity, the total outside size of the cable, and that perhaps requires, under some conditions, an increased pipe. In the case for which the cable I refer to was made, the pipe was already in existence, and the cable is not now big enough to fill the pipe, so that the pipe is there and the cable is not big enough to fill it. That you will find in practice will often be the case. If you have a pipe that will carry 300 conductors and you only want to put 50 conductors in it, there is no use in saying the pipe will cost you more

until you arrive at the time when you are carrying such a large number of wires that you must have a larger one. But there are a great many cases where that does not exist, and therefore I think a great many situations where continuously loaded cable could be used giving a very great improvement indeed. The cost of that improvement, leaving the consideration of the pipe out of the question, is, as near as I can calculate it, this: you get at least 100 per cent. improvement from the speaking point of view at an extra cost of 50 per cent., and that, by using a quantity of iron on the copper, just equal to half the weight of the copper. At the moment I am not prepared to say whether 50 per cent. of iron to copper is the right amount. We are sure that if you put more than that on you will do harm; we are not sure if you put less than that on you will not do more good, but it requires further experiment. As a member who at one time attended these meetings pretty regularly a few years ago, I remember there was always one point thrown out in the discussions, namely, that the mathematician never obtained very liberal encouragement from the practical engineer as to what work he should do. I suggest that here is a case where the electrical engineer or manufacturer is dying for a mathematician who will tell him what the improvement will be on the one side, or the loss will be on the other, when he varies the iron in proportion to the amount of copper used. That will save him a lot of expense. Instead of having to find it out by manufacturing a long length of wire, if the mathematician can tell him on a sheet of paper what the result will be, the manufacturer will be only too glad to meet the mathematician. Then we could all work together, shake hands, and hope we would arrive at a good result. I do not know that I have any more to say except this, that I feel the absence very much of what I would call the master mind on this subject from our meeting to-night —I refer to Mr. A. W. Martin of the Post Office. I have read his work in connection with this subject with very considerable interest. I do not remember any work or paper that created more excitement at the back of my head than Mr. Martin's work on this subject, since the old days when Professor Hughes showed us the difference between resistance when measured by high-frequency currents and by steady currents. Mr. Sinclair.

Mr. F. TREMAIN: Perhaps I may be allowed to explain that the composite-core cable, illustrated in Fig. 14, which I designed in 1901, and details of which are given in Appendix V., had an actual capacity from wire to wire of 0·107 microfarad per knot, a resistance of 1·419 standard ohms, and an insulation, when manufactured, of 12,571 megohms per knot, compared with wire-to-wire capacity 0·1375, and a resistance of 7·209 in the case of the Anglo-Belgian cable, which was, I believe, manufactured at about the same time. The exceptionally large conductor was used in the experiment in order to determine the maximum size with which a low capacity could be obtained, and it was recognised that in practice a smaller conductor of the same type would probably be used. The intention was to provide not one circuit as Mr. Tremain.

Mr. Tremain.

indicated in Appendix VIA. but two, the second being made available by the use of suitable transformers at the cable ends, by which the two conductors could be used as one for a second circuit with the sheathing of the cable as a return; hence the helical winding of paper cord outside the pair of conductors to keep them away from the rubber dielectric, and ensure a reasonable capacity from the two conductors to the sheathing. As a matter of fact, this capacity proved to be 0·256 microfarad per knot for a 1,650-lb. conductor. My proposal was to lay a cable of this type from a point near Felixstowe to the nearest point on the Dutch coast, the object being to provide a telephone service between London and the principal Dutch towns, as well as to German seaports, and more particularly Berlin. The experimental length was manufactured in January, 1902, and I find from my notes during manufacture, that it was intended to leave the conductor round for about 3 yards from the ends of each length, and discontinuing the paper and rubber in order to seal each section with gutta percha, so that loading coils might be inserted to be completed over all at the joint with gutta percha insulation. A special type of loading was designed, and it was stipulated that the iron cores of the loading coils should not exceed 3 mils in diameter. I also made experiments at this time to prove that both phantom and physical sets could be loaded. The 1,400 lbs. of gutta percha used in manufacture was thought at the time to be heavier than was necessary. It will be observed that from the sample there are two separate servings of gutta percha with a brass tape between. This construction was not found altogether satisfactory, and the outer covering of gutta percha had to be made thicker than would otherwise have been necessary consequent on the tape being embedded in that material. It was therefore decided that in view of the layer of rubber provided within the gutta percha the outer layer of gutta percha could be entirely dispensed with, and the inner coating reduced, the brass tape being placed outside the dielectric in the usual way. As the inner layer of gutta percha weighed 875 lbs. per knot, and the outer layer 580 lbs. per knot, it will be seen that the total quantity of gutta percha would be approximately half that indicated in Appendix VIA, and the cost of the cable materially reduced. Of course, in the case of the first, second, and last cables mentioned in Appendix VIA, the weight of gutta percha for each conductor is given, and I think the cable of my design would, as a matter of fact, have a considerably smaller quantity of this material than the other cables mentioned. At the prices quoted for copper and gutta percha, I notice that in the first-named cable the cost of these materials is £430, and in the Anglo-French cable £321, whilst in the one of my design—including £70 for rubber—the cost is £480. The estimate of £1,145 is, therefore, very high, and must, I think, be based on higher prices. The attenuation constant per knot for the Anglo-French unloaded cable being 0·0766, the air-spaced cable under consideration is about 2½ times as efficient. As the shortest distance between England and Holland is a little more than twice that between Dover and Calais, we

should have obtained by the use of this cable as good a service to German towns as that provided between England and France. Unloaded, it would have allowed of communication with the greater part of the German and Austrian Empire as well as with places in Denmark, etc.; and, if loaded, of communication through German territory to the Russian capitals. As regards the practicability of this cable, it is true that with time the paper absorbs the moisture from gutta percha through the rubber, but it was thought not to be impossible to find a dielectric other than paper which would not absorb moisture, and in this design the specific inductive capacity of the insulation would not be of the same importance as in the case of solid insulation, as the greater part of the area between and around the conductors is air-space. Perhaps I may be allowed to express my indebtedness to Messrs. Henley's Telegraph Works, Ltd., for making the experimental length, which I venture to think may yet be the basis of a working cable. Mr. Tremain.

As to the economic aspect of the question, too much emphasis may be laid on the cost of cables in view of the costly land lines with which they must be associated. The author has told us that with conductors weighing 800 lbs. to the mile it would be possible to establish communication between London and the shores of the Caspian Sea. If open wires of this extent are required to feed a cable with traffic (and seeing that these lines would not only run in one direction or be provided on one side only of the Channel), I think we may assume that the share of the heavy aerial wires utilised by each submarine circuit would not be less than, say, 2,240 miles. As the pair of wires weigh 1,600 lbs., these circuits involve the use of 1,600 tons of copper, which, at £75 per ton, would cost £120,000. If to this be added the cost of the pole-space occupied by a pair of wires—say, £20 per mile—the cost of the aerial line proper to one submarine cable pair would not be less than £152,000 or £300,000 for such cables as those under discussion. Whilst, therefore, it appears perfectly sound to ascertain with care the cheapest submarine cable possible for a given efficiency, it might conceivably be worth while to pay a considerable sum for a slight improvement, as it might effect an actual saving by rendering possible a slight reduction of gauge over these great distances, or render possible a further extension of, say, 50 miles radially, and open up a wide belt of additional territory for revenue-earning purposes. A 5 per cent. saving on the aerial line costs above referred to would pay for the entire cable from shore to shore.

Concerning the feasibility of loading aerial lines, I should like to point out that, apart from the difficulties of climate which have to be contended with in this country and, probably, on the Continent, a pair of loaded wires is likely to be much more susceptible to interference from outside sources than an unloaded pair, being as it were in a hypersensitive condition.

Sir John Gavey spoke of the reduction of the effective conductivity of heavy conductors in this country by the introduction of protective

Mr. Tremain.

devices as being nearly 20 per cent., but I think it will be found that from this and other causes the depreciation is much greater, chiefly, of course, due to the difficulty of getting open lines erected in the cities and towns. I believe it is a fact that the London-Glasgow telephone wires—a pair of which weigh 300 tons and which theoretically should equal 9 miles of standard cable—in practice are only equal to 14 miles of standard cable, and it is deplorable that the unreasonable restrictions of local authorities to the erection of open lines should have involved the expenditure of enormous sums for additional copper, which would not otherwise have been necessary. I presume the author anticipates getting his 800-lb. conductors erected throughout Europe without the interpolation of lengths of underground which would render communication over the distance he mentions well-nigh impossible.

We are all, I am sure, grateful to Mr. Kempe for his efforts to simplify the application of these complicated formulæ, and his table of telephone loops in terms of centibetas well repays studying. It is rather alarming, for instance, to find that nearly half the total recorded as the limit of commercial speech is absorbed in Exchanges and subscribers' lines, and leads one to doubt the wisdom of the policy of placing at the disposal of all local subscribers the long-distance service. If special circuits were provided for long-distance users or, as an alternative, they were required to attend at the Trunk Exchange for their business, it would evidently be possible to effect very considerable economies in the long-distance plant and increase the area of territory in which telephonic communication could be possible. No one could take exception to the new terms he suggests, but a previous speaker is, I think, less successful. Apart from the danger of confusion likely to arise due to the use of the term "knot" for length, the term he suggests for nautical mile is not euphonious. I have recently been working out the attenuation constant for various circuits, and have had to use many noughts. If I had also used the term "nauts" instead of "knots" I fear confusion might have resulted. I am afraid that in the Post Office the use of "knot" for this purpose is almost ingrained in our nature. It is thus used in Merryfield's "Navigation," Clark and Sabine's Tables, Latimer Clarke's "Metric Measure," and in some encyclopædias and dictionaries. As a way out of the difficulty I would suggest that we adopt the title "Siemen," a name we all delight to honour.

I find on looking through some of my experimental note-books that early in 1901 inductive shunts were tried by me on a cable 39 miles in length, the cable being bridged in the first instance at approximately half-mile points, 43 inductances each measuring 5¼ henries being used. No increase of volume was apparent, but the articulation was thought to be a little clearer than through the unshunted cable. At intervals of 2 miles—the individual value of the inductances remaining the same—the speaking was thought to be distinctly better with a very slight increase in volume. At intervals of about 4 miles, ten inductive shunts, the speech was not quite so good as before, and a further

reduction produced still worse results. The improvement was so slight compared with that obtained with much smaller inductances in series, whereby a 2¼ to 3-fold improvement was obtained, that the experiment with inductive shunts was not further pursued. Mr. Tremain.

Mr. B. DAVIES: I am sorry to say that Mr. Judd, who intended to be present this evening and say a few words on loaded-line experiments carried out at the Laboratory of the Associated Telegraph Companies at Electra House, is unable to be present to-night, and therefore with your permission I will refer to those experiments very briefly. The object at the outset was to produce a distortionless cable. The experiments were suggested by Sir Oliver Lodge, and were carried out in 1904–5. An ordinary submarine type of artificial line was adopted for the experiment. Into this were introduced inductances at regular intervals along its length. These inductances were ironless, and were variable. Leakances were also introduced at similar intervals, those intervals being represented by about 3 microfarads of the line. The interval corresponded with about a 10-naut length of cable of mean thickness. The leakance could be varied in resistance from zero up to 1 megohm, and the inductance could be varied from zero up to about 1 henry. The conductor of the cable itself could also be varied considerably, so that we had an arrangement that was comfortably flexible. The results obtained were interesting, and threw a flood of light on the problem. The cable became extremely lively when adjusted to the distortionless state. It was almost my first experience in submarine telegraphy, and I remember well my astonishment in seeing the signals issuing at the distant end very much of the same character as they were sent in. The signals at the receiving end needed little or no correction in the way of shaping, the line acting almost as an ordinary aerial line. From the distortionless point of view the experiment was successful. But, unfortunately, although the signals came out very crisp and sharp, they were very attenuated. The attenuation really became serious. What happened obviously was this, that the product of the resistance and capacity—that trouble which is the main trouble of the telegraph engineer—was avoided, but another trouble was encountered, that was the product of resistance and leakance, and the one is just as vicious as the other, telegraphically. The leakance component could, of course, be reduced by increasing the inductance, but it was not considered feasible in practice to load the cable to a greater extent than 0·03 henry per naut. Owing to our inability to increase the inductance the distortionless cable had for the time to be abandoned. A cable loaded with 0·03 henry per naut, and rendered distortionless by the application of appropriate leakance, could not be worked in practice under existing conditions of sending and receiving if its length exceeded that corresponding to 1½ seconds of plain cable. The next step was to try experiments on the loaded cable without leakance. These experiments were considerably more promising, because here the attenuation was reduced to something considerably lower than the normal for the plain cable. Mr. Davies.

Mr. Davies.

TABLE I.

Comparison of Plain with Loaded Cables without Leakance.

No. of Cable.	L in Henries.	μ.	Observed Speeds in Letters per Minute.		
			S R = 1·54 sec.	S R = 2·4 sec.	S R = 3·2 sec.
(1) Unloaded ...	0·000	1	340	280	220
(2) Loaded ...	0·019	150	600	340	—
(3) Loaded ...	0·032	250	800	440	370

The table shows the observed speeds of three cables—viz., first, a plain cable; second, a cable furnished with inductance equal to that which would be given by cable (1) if wound with iron wire to a diameter of 1·4 times the diameter of the copper, the permeability being 150; and, third, a cable similar to (2) but with $\mu = 250$.

If now the space occupied by the iron load be filled with copper, the speeds for the three cables will be as follows (neglecting disabilities of receiving instrument at the higher speeds):—

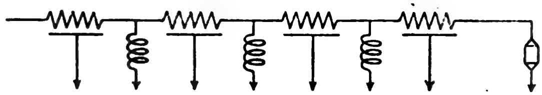
TABLE II.

Speeds obtainable on all-Copper Cables, the diameter of the Copper being the same as that of the Iron Load in Cables (2) and (3) of Table I.

	S R = 1·54 sec.	S R = 2·4 sec.	S R = 3·2 sec.
Speed in letters per minute ...	680	560	440

Comparing cable (3) Table I. with the all-copper cable of Table II. we see that for the S R = 1·54 sec. the loaded cable (when $\mu = 250$) is 18 per cent. superior in speed to the plain cable. For the S R = 2·4 sec., with $\mu = 250$, the all-copper cable is the better by 27 per cent. The situation is thus reversed. And lastly, for S R = 3·2 sec., the all-copper cable beats the loaded one by 19 per cent. The distributed load was therefore abandoned, because the all-copper cable is mechanically simpler than the loaded one, and, possibly, not more expensive. We did not try, except in a very elementary way, the idea suggested by Dr. S. P. Thompson, that is to say, the inductive leak. That would have been interesting, because this cable has a power of discrimination which the non-inductive leak cable has not. Such a cable would hand on, as it were, the rapidly varying part of the signal, but leak to earth the slowly varying, distorted part. But I fear that in practice the resistance of the leakance would have to be put up so much that the

inductive component would become suppressed. With an inductive leak of low resistance the cable would act in a curious way, giving a peculiar kind of distortion. If you will allow me, I will show this on the board. Dr. Thompson's cable, reduced to its simplest form, would, I think, appear as shown in Fig. A. In a cable with inductive leak, if the resistance of the leak be low, a signal of the form shown in Fig. B sent into the cable would be turned at the distant end into a signal of the type shown by Fig. C, the cable acting as if it were made up of a series of condensers. And I fear that before the signal could be properly shaped at the distant end—that is to say, be converted into that of Fig. B—the resistance of the leak would have to be high, and therefore we should have an inductance leak with a very large resistance component, and an inductance component correspondingly suppressed. In this condition the cable would act almost as a cable furnished with non-inductive leakance. Such a cable, however, would have a better chance of success if used for telephony, in which frequencies are high, rather than for telegraphy, in which frequencies are low. Mr. Davies.



A

B

C

Figs. A, B, C.

In 1905, after the completion of the experiments on uniformly loaded cables, a new course was taken. It was found at Electra House that an inductance of considerable value could be inserted at any point in the cable with great advantage. The size of the load so used varies according to speed and type of cable, and earthing, from about 4 henries to 40 henries and more. This concentrated inductance method could be immediately utilised for traffic purposes on existing cables, for it could be applied to both ends of the cable, as well as at the landing-points of two sections of a cable. The advantage gained by the use of concentrated inductances in mid-cable varies from 7 to 10 per cent. for each inductance introduced. It was found that the value of the inductance to be placed at the beginning of the cable was, approximately, $L = 0{\cdot}48\, p^{-\frac{3}{2}} (R/S)^{\frac{1}{2}}$ for simplex, where p has the usual meaning ($= 2\pi n$). Subsequently Mr. Judd suggested the use of a condenser S' in series with such an inductance. The value of the inductance then becomes—

$$L = \frac{1}{2p^2}\left[\frac{5}{4S'} + 0{\cdot}707\, p^{\frac{1}{2}} \left(\frac{R}{S}\right)^{\frac{1}{2}}\right]$$

for simplex, and this is the system now largely in use on the com-

Mr. Davies. panies' cables. The constants 0·48 and 0·707 are both empirical. R/S is the core ratio. We found that the effectiveness of the inductance depended largely on the character of the iron magnetic circuit; closed magnetic circuits were useless. I would like to ask the author if this question of the type of magnetic circuit has been definitely settled with regard to coils used in telephony. There is also another point in this connection that is of some importance in this present paper. On page 318 a statement is made concerning the eddy currents in a uniformly distributed load. From the construction of the cable one would hardly expect the eddy-current trouble to be so great. May I ask the author if the loss is experimentally proved to be due to eddy currents? Another interesting fact in the paper is the absence of distortion in the Anglo-French cable at a frequency of 750, due to the existence of a defective property of the dielectric—viz., the apparent leakance. The apparent leakance simulates the effect of real leakance for this frequency. But the column for $e^{\beta l}$ on page 355 shows that the cable is far from being distortionless for the higher frequency of 1,720. It would be interesting to know what variations in the four quantities concerned—viz., resistance, inductance, capacity, and leakance, are responsible for so great a distortion at 1,720, even greater, relatively, than that produced by a plain cable.

Mr. Cook. Mr. W. W. Cook: The Postmaster-General referred to the author's imagination, and I think a little of that imagination has crept into the statement that very satisfactory conversation is now possible between London and Astrakhan. I was going to ask the author why he stopped at Astrakhan, but we learn on the Postmaster-General's authority that he has not done so; he has gone on to Calcutta. Unfortunately the Postmaster-General did not disclose the means of getting there, but probably it would be by means of loading the land wire. But the author is quite definite with regard to the way to get to Astrakhan; it is by means of 800-lb. unloaded land lines and the Anglo-French cable. Now I have no doubt that at some future time conversation will be possible between these two important places, but I do not think that a gain of 7 standard miles on the Anglo-French cable justifies us in straying so far afield as Astrakhan, whilst in practice there are so many large cities so much nearer home with which we cannot communicate. I think in this statement the author has not attached sufficient importance to the point raised by Sir John Gavey at the last meeting about the material reduction of the effective conductivity of these long land lines. Sir John Gavey gave the reduction as about 20 per cent.; Mr. Tremain to-night has given us figures of an actual case which show a reduction of nearly 50 per cent. A few years ago there was a circuit from London to St. Margaret's Bay—I do not know whether it has been altered since—of which, out of the total distance of 85 miles, 79½ miles were 800-lb. conductors, the remaining 5½ miles being made up of smaller conductors. If in that land line 400-lb. copper had been substituted for 800-lb. leaving the remainder as it was, that would have saved 28½ tons of copper, and it would have involved a loss of

Mr. Cook. an equated length of $1\frac{1}{2}$ standard miles. But having already lost $1\frac{3}{4}$ standard miles in the smaller conductors, it seems to me it would be more economical to spend money in improving those rather than in increasing the weight of the copper to the extent mentioned.

I think the influence of loading submarine cables must have a very important bearing on the communication between England and Ireland. At the present time the method of getting from the South of England to the South of Ireland is round by Scotland. That is quite accounted for by the comparative efficiencies of the land line and the submarine cable; but if the latter is improved to the same extent as the Anglo-French cable, so much money will not be able to be spent on the long land lines, and therefore it will probably pay to take a more southerly route when additional lines are required. Perhaps the author will tell us whether that point has been gone into already. From the historical point of view the tests on the Irish cables described on page 313 are very interesting. It is only by going back to tests like this that one realises the immense strides that were taken directly quantitative measurements were possible. For the benefit of the future historian, I would suggest to the author that he should insert a footnote making it quite clear that the results that are given on pages 313 and 314 were arrived at in 1900, and not at a later date. For the same reason I think he might with advantage describe the type of instruments used in those tests. There is one point in those tests that rather puzzles me; it is stated that speech was just possible between experts over a distance of 120 "Siemens." I think it would probably get me out of my difficulty if the author would give the equated length of that circuit. I make it about 95 standard miles, and if that is correct, I think the talk between London and Astrakhan is a mere nothing. I also wish the author would give us the results of the tests that were made at a later date, because they would no doubt be expressed in much more definite terms than was possible in 1900. I was going to ask the author for some particulars of the cable shown in Fig. 14, but those have already been given by Mr. Tremain. The author may possibly have given the cost a little too high, but when we consider that the attenuation constant given for that cable is twice that of the Anglo-French cable, and the cost of the two-core cable is twice as high as the four-core loaded cable, it will be seen that the cost will have to be reduced a great deal before that type of cable becomes practicable. There is just one other point I would like to ask the author, namely, why on page 340 he has included the last column but one, and why he has given it that description. It is described as an old formula, but it is given a new name; and when people suddenly change their name without giving notice, one is apt to think that there must have been something shady in their past history. I think that is probably true in this case. That old formula, as you will see, is the product of two colums in the table; they are disguised by C' and γ, but the formula is really KR.

Mr. Campbell.

Mr. ALBERT CAMPBELL: Major O'Meara's present contribution to the somewhat scanty literature of submarine telephone cables is both important and most interesting. As the subject is one in which practical data are still scarce, I take the opportunity to give here some of the results of tests on a variety of experimental samples of telephone cables, which we have carried out at the National Physical Laboratory. The lengths tested varied from 10 metres up to 400 metres; in most

TABLE A.

(Lbs. per naut = 4·1 kg. per km.)

Cable.		Diameter.	Kg. per Km.
		Milimetres.	
U	Solid copper core	2·67	277
	Lapped with 10 copper wires, each 1·12 mm. diameter ...	—	
	Gutta percha to	10·9	152
V	Solid copper core	3·5	—
	Lapped with 4 iron strips (side by side) 2·7 mm. wide by 0·5 mm. thick	—	—
	Gutta percha to	10·8	—
W	Copper Core	3·52	172
	Braiding of thin iron and copper wires about 0·02 mm. diameter to	5·47	52 (iron) 56 (copper)
	Gutta percha	10·9	147
X	Copper core	2·03	—
	Lapped 1 layer of iron wire of 0·12 mm. diameter ...	—	—
	Paper insulation	—	—
	Lead covering two cores to...	12·5	—
Y	Same as X, but with two lappings of iron wire ...	—	—
Z	Copper core	2·03	—
	Distance between cores, 5 mm.	—	—
	Lapping, two layers of iron strip 0·12 mm. thick, (skew width, 2·4 mm.)	—	—
	Paper insulation	—	—
	Lead covering to	13	—

cases accurate results could be obtained with lengths of 20 (or even 10) meters, and the agreeement between the measurements on long and short lengths was quite satisfactory. The four important constants, namely, the effective resistance R, effective self-inductance L, capacity K, and effective leakage conductance (leakance) G, were measured for various frequencies, and were taken per kilometre of length of loop (total length of conductors = 2 km.) The measurements of R and L were made simultaneously by the help of a direct-reading mutual in-

Mr. Campbell.

ductometer of long range from 0·01 microhenry up to 4,000 microhenries, the effective resistance being balanced by a constant inductance rheostat*; for short lengths it is not desirable to trust to the readings of the rheostat, so the value of each setting is checked by switching it on to an ordinary Wheatstone's bridge. The K and G were measured against an air condenser, or a mica one with very small leakage, by Wien's method, in which the leakage of the cable is balanced by a quite moderate resistance in series with the standard condenser.† The source of current was a wire interrupter for the lower, and a microphone hummer for the higher frequencies. Especially when short lengths are being dealt with, it is necessary to guard against electrostatic effects to earth; this source of error is almost entirely eliminated by having an earthed screening coil between the primary and secondary windings of a transformer connecting the bridge and the source. The particulars of the cables were as follows. In U, V, and W the two lengths were twisted together, covered with hemp, and taped; the covering was wet during the tests. Cable X, Y, and Z would possibly not be classed as submarine; they are lead-covered.

In Table B are shown the results of some of the measurements. The attenuation and wave-length constants for 1 km. being given by the equations—

$$2\beta^2 = 2\,(\text{atten. const.})^2 = \sqrt{(R^2 + L^2\omega^2)(G^2 + K^2\omega^2)} + RG - \omega^2 LK$$

and—

$$2\alpha^2 = 2\,(\text{wave-length const.})^2 = \sqrt{(R^2 + L\omega^2)(G + K^2\omega^2)} - RG + \omega^2 LK,$$

where $\omega = 2\pi n$.

I may here remark that there is at present some confusion amongst writers as to the nomenclature of these two constants. I have used α and β in the same sense as in Major O'Meara's paper, and possibly this is the most generally accepted usage; but the opposite usage, making α and β the attenuation and wave-length constants respectively, seems to me more reasonable.

The values of the attenuation constants in Table B on the whole corroborate those given by the author for continuously loaded cables. The measurement of the leakance G is much the most difficult part of the experiments; fortunately it does not influence the value of the attenuation constant to any great extent. Its increase with frequency is shown clearly over a long range for cable W.

In connection with cable Z we investigated the effect of the condition of the iron. Samples of the thin strip were wound into small rings which were tested magnetically by the ballistic method, going down to very small values of H so as to obtain values of the permeability μ corresponding to those occurring in actual telephone cables. The values (μ_0) of the permeability for H = 0 may be taken as the working values for currents of the order of those used in

* *Philosophical Magazine*, vol. 15, p. 155, 1908.
† *Electrician*, vol. 64, p. 350, 1909.

Mr. Campbell.

telephonic practice, since with the actual mean diameter of the iron lapping (0·2 cm.) we have—

$$H = 2 \times \text{current}.$$

In Fig. D the curves refer to iron strip in the following conditions:—

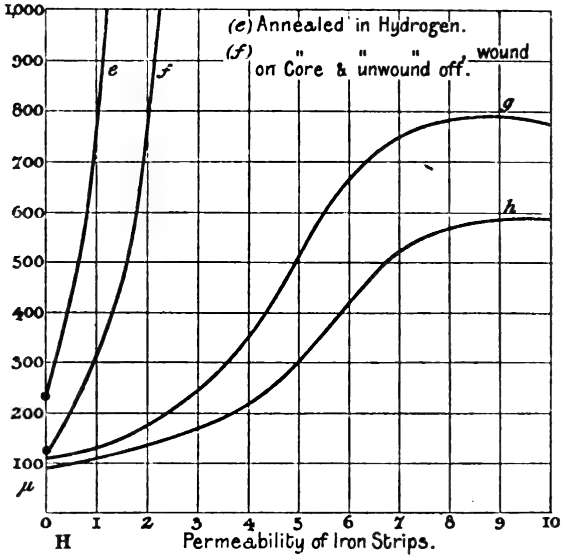


FIG. D.

(*e*) Annealed in hydrogen.
(*f*) Annealed in hydrogen, wound on core and unwound off.
(*g*) Partially annealed and treated as (*f*).
(*h*) Unannealed.

We also tested the self-inductance of a 1-metre length of the cable core—

(*a*) In condition as received.
(*b*) After annealing the whole piece in hydrogen at 850° C.

From the values of the inductance thus obtained (with small H) the initial permeability (μ_0) was calculated in each case. The results were in agreement with those given by the ballistic method, the value of μ_0 being for (*a*) 125 and for (*b*) 235. In Fig. D these points are shown by small circles.

Thus it is seen that the thorough annealing raised the working permeability from 125 to 235. By recalculating on the basis of this improved permeability, the attenuation constant for $n = 1{,}000$ is reduced from 0·0149 to 0·0114. It was found that if the strip was only

Mr. Campbell.

TABLE B.

Cable.	Iron Loading.	Insulation.	Frequency n per Second.	R Ohms per Kilometre.	Henries per Kilometre.	10^6 K Microfarad per Kilometre.	10^6 G / Ohms × Kilometre.	Attenuation Constant.	Wave-length Constant.
U	None	Gutta percha	500	2·3	0·00072	0·106	15	0·0134	0·030
			1,000	2·4	0·00071	0·106	20	0·0150	0·056
			2,000	2·5	0·00071	0·106	40	0·0166	0·110
V	Strip	Gutta percha	200	3·46	0·00372	0·103	1·4	0·0086	0·026
			1,000	5·9	0·00368	0·100	10	0·0167	0·128
			2,000	11·65	0·00350	0·100	25	0·0330	0·236
W	Thin wire	Gutta percha	15	2·98	0·00247	0·123	—	0·0040	0·0051
			60	2·99	0·00247	0·122	0·74	0·0072	0·0097
			120	3·01	0·00247	0·122	1·49	0·0089	0·0157
			200	3·08	0·00246	0·121	2·86	0·0100	0·0238
			500	3·52	0·00243	0·119	10	0·0127	0·055
			1,000	4·61	0·00236	0·118	19·8	0·0174	0·106
			2,000	8·66	0·00218	0·116	45·9	0·0343	0·203
X	Wire (1 layer)	Air-paper	200	10·5	0·00235	0·0416	5	0·0212	0·065
			1,000	10·7	0·00234	0·0408			
			2,000	11·1	0·00227	0·0416			
Y	Wire (2 layers)	Air-paper	200	10·6	0·00422	0·0414	4	0·0167	0·084
			1,000	10·9	0·00419	0·0410			
			2,000	11·4	0·00417	0·0415			
Z	Strip (2 layers)	Air-paper	200	10·8	0·00576	0·0410	Less than 1·2	0·0122	0·027
			1,000	11·3	0·00572	0·0414		0·0149	0·098
			2,000	12·7	0·00567	0·0415		0·0169	0·194

Mr. Campbell.

annealed before being wound on, the benefit of the annealing was almost annulled by the mechanical treatment (bending, etc.) during winding, but this is by no means an insuperable difficulty in manufacture. In this connection I have sometimes recommended the trial of silicon iron or other alloys, which have large initial permeability and high resistivity, since every reduction of energy loss seems likely to improve the conditions. In conclusion, I would express my best thanks to Sir John Gavey and Mr. R. K. Gray for their kind permission to publish the above results.

Mr. Mordey.

Mr. W. M. MORDEY: I am very glad that we have a telephone paper of this character before us, and that the question of loading—not a very happy term—has come up for discussion. I do not presume to express any opinion on the question of the best method of loading of cables. It seems to me that we are only on the threshold of the subject,

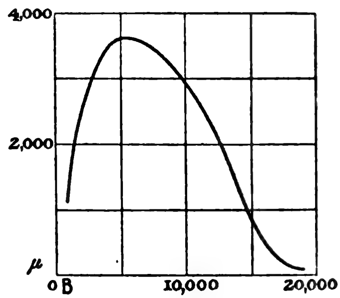


FIG. E.

which is very important and far-reaching, not only for telephone cables, but also for telegraph cables. I cannot help thinking that it is much too early to attempt to dogmatise and to say that distributed loading is never going to be a success. One naturally agrees in principle with Dr. Thompson's remark at the last meeting, that a distributed fault calls for a distributed remedy. It probably will depend very much on the character of the loading material. Mr. Campbell's tests are interesting; they are tests with ordinary iron. I do not gather that he has specially investigated the region where, I presume, we would have to work—the region approaching the horizontal, at the very beginning of the permeability curves of iron. I would like to show you some results of tests to illustrate the conditions of the important material, the iron. This region has been explored by Ewing and Lord Rayleigh, but it has not been studied or considered very much. At the last meeting but one we had a paper by Sir Robert Hadfield and Professor B. Hopkinson which increased our knowledge of the magnetism of iron in very intense fields, and I then ventured to suggest they should turn their attention to this lower region and endeavour to find a material with a high permeability near the origin.

Fig. E shows an ordinary permeability curve of stalloy, which is mainly a silicon iron. I think it is better to use μ-B curves, as they are more illustrative than B-H curves. You see the permeability goes up to about 3,600, which occurs at about B = 5,000. For the present purpose, I imagine, we require to go down to an induction of a very few lines. Fig. F. shows the results for the same material at very low values. Take the very bottom of the lower curve; there you have B going up to 2. You see that the induction is proportional to the magnetic force: if you look higher up you will see, on a much larger scale, a little more of what happens. The permeability is constant at about 320. There is a very interesting thing there. The dotted line shows the retentiveness. Mr. Mordey.

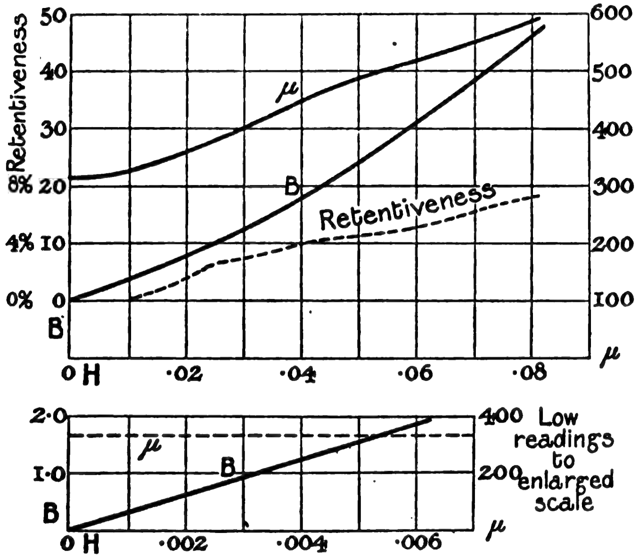


FIG. F.

You will see that up to an H of about 0·01 there is no retentiveness at all. If that is right—and there are good and well-known reasons for believing it is—it means there is no hysteresis there. It is somewhere in that region that I suggest successful continuous loading, if it is ever attained, may be reached. The amount of energy available for these cable applications is so minute that the question of loss of energy must be of the first importance—therefore there should not only be a high permeability, but that there should be a very low hysteresis, or no hysteresis, and a very high specific resistance in the loading interval. This material is a very encouraging one from this point of view, as its specific resistance is high, something like 40 to 60 microhms per cubic centimetre, very much higher than iron, and its ordinary hysteresis is very low. Decreasing the losses in the iron is equivalent to increasing

Mr. Mordey.

the section of the copper. That is to say, decreasing the loss in the loading material is the same as lowering the resistance of the copper itself. I need hardly say I cannot tell telephone people anything about loading cables, but I hope these curves may interest them, as a study of the properties of the material at very low values under the very small magnetic forces that may have to be employed in this kind of work. Something was said by one of the speakers last time about the decrease of permeability caused by winding the wire on. Judging from tests before and after applying a tension of 15 tons per square inch, I do not think the winding will decrease the permeability appreciably, but it will increase the hysteresis, and to this must be added the effect of bending, which we know may also increase the hysteresis. Although it has no special bearing on this subject, I might mention that I pointed out in a paper in 1895* that compression caused a large increase in the loss of energy, which disappeared entirely when the pressure was removed—unlike the effect of tension, which, unless kept within the elastic limit, can only be removed by annealing, which, of course, would be impracticable.

Mr. Granville.

Mr. W. P. GRANVILLE: The Post Office engineers have unique opportunities for experimental research in telephony, and I think we ought to congratulate ourselves that Major O'Meara, in his most interesting paper, has kindly given us some of the results obtained. With regard to the recently laid Anglo-French cable, I should like to point out that nearly two-thirds of the benefit gained by the use of the inserted inductance coils might, at the same money cost, have been readily obtained by simply changing the weights of copper and gutta percha from 160 lbs. and 300 lbs. per mile to some such proportion as 400 lbs. and 270 lbs. respectively — and that without the use of added induction coils. Probably the reply to this statement will be that such a ratio of copper and gutta percha would produce the "drumminess" referred to in the paper, but this effect does not appear to be a very serious one, for reference is also made in the paper to a speech test made on one of the Irish cables (60 miles in length), and it is there stated that the articulation was "very well defined," although in that case the ratio of capacity to resistance was nearly double the minimum value at which "drumminess begins to be unmistakable." But even if we take it for granted that inductance loading must of necessity be used, not only for the purpose of obtaining the maximum improvement in the attenuation but also for getting rid of the "drumminess," still, surely, it would be of great advantage to have this altered proportion of copper to gutta percha, because it would enable the maximum gain to be obtained with only 20 millihenries of added inductance, instead of the 50 millihenries rendered necessary by the use of the smaller conductor employed in the Channel cable. This is important, because the smaller amount of inductance necessary would mean fewer inserted coils, and these spaced at wider intervals; thus the mechanical difficulties would be considerably reduced, and, in addition, there would be an improvement

* *Proceedings of the Royal Society*, vol. 57, p. 224, 1895.

Mr. Granville.

in the "attenuation" of 25 per cent. over that given by the "loaded" 160–300 core actually used. But if this additional 25 per cent. improvement is unnecessary, then the same attenuation value as that which rules in the Channel cable could, in the case of the 470-lb. conductor, be obtained by the addition of only 7 millihenries of inserted inductance per mile.

Reference has been made in the paper to the "air-space" cable devised in 1897 by Mr. Willoughby Smith and myself and laid across the Irish Channel from Wales to Ireland. The author referred to the fact that in that cable the articulation was particularly good, but that there was a serious defect due to "cross-talk." I should like to point out that we were then dealing with equal weights of copper and gutta percha, and that if we had used the liberal proportion of gutta percha that is used in the present form of Post Office cable, namely, nearly twice as much gutta percha as copper, in that case the articulation would have been still further improved, and in all probability the defect of "cross-talk" largely eliminated. Looking at the whole subject from the practical point of view of one closely in touch with the actual manufacture of submarine cables, I am inclined to think that for the future we must look to larger conductors, slightly loaded, and probably to some form of air-space; and when we think of lightly loaded conductors we naturally turn to the continuous form of loading introduced by the late Dr. Krarup, and now in use on the Continent.

Mr. Cohen.

Mr. B. S. Cohen: There are several points in this very interesting paper to which I should like to refer. With regard to the drumminess ratio $K/R = 0{\cdot}003$ (where, by the way, K is in microfarads and R in ohms) all the work of the National Telephone Company has confirmed that figure. It is worthy of note that a 70-lb. conductor dry-core land cable attains that drumminess ratio; and this is an additional argument, if any were necessary, in favour of using light conductors loaded pretty heavily instead of heavy and unloaded conductors. The author states that in the Anglo-French loaded cable the coils were placed at one knot distance, and the two end coils were placed half a knot from the ends. Now that is the general practice in loading land lines where they are terminated by short lengths of unloaded cable. In the case of the Anglo-French cable where, I take it, it is normally used with a long length of unloaded open wire line at each end of it, I venture to think that even a greater improvement might have been obtained than was secured had the two end coils, instead of being placed half a knot away from the ends of the cable, been put in the huts on either side of the channel. Keeping the same spacing as at present, one extra coil would have been used, and two coils would have been taken out of the sea; and by rough calculation I think a 10 per cent. improvement over what has been obtained would have resulted. There may be some reason in this case against the adoption of this practice, and perhaps the author will say whether he considered that point or not. Then with regard to the question of the importance of leakance in connection with loaded lines, that has been mentioned in the paper, but nothing

Mr. Cohen. definite has been given in regard to the matter. Some time ago we had occasion to consider a case of 200 miles of 200 lbs. open copper line. This particular line was very heavily loaded to 0·052 henries per mile: and some curves were calculated in order to see the effect of leakance on this line when loaded and unloaded. I should like to show the following slide (Fig. G) in connection with this matter. It will be seen there are two curves, one for the loaded line and one for the same line unloaded, and we have as abscissæ the insulation resistances in megohms per mile, and as ordinates, equated lengths in standard miles; it will be seen that at an insulation resistance of about 0·2 megohm, the loading was of no advantage, whilst at about 2 megohms the loading is very nearly as efficient as if the line insulation were infinite. With a more suitable, lighter loading, there should be no insuperable difficulty in maintaining this line as an efficient insulation.

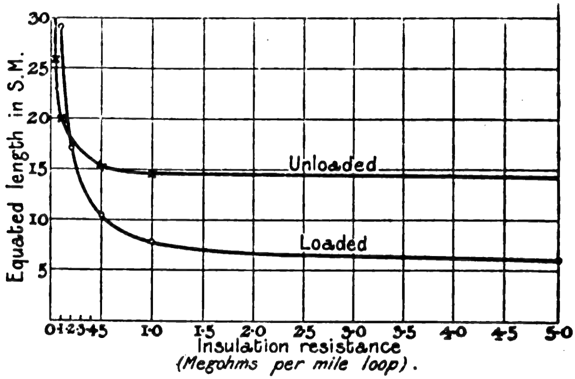


FIG. G.—Effect of Insulation Resistance on Transmission.

A statement is made on page 348 that it has so far not proved possible to design a loading coil with an effective resistance below 6 ohms per 100 millihenries. I would point out that in America an aerial line-loading coil, with an effective resistance of about half this value, has actually been employed by the Western Electric Company for some years. On page 349 a doubt is expressed as to whether the attenuation constant of a standard cable is really 0·103. Now, that is the actual value at 750 ∿. If we take the frequency of $5,000/2\pi$, which is in a fair way to being adopted internationally, the attenuation constant is 0·107, but the alteration is merely due to the change of frequency. With regard to the proposals for new units, I think it will be found, as Mr. Gill and other speakers have mentioned, that there are some serious objections to departing from the standard mile, and I cannot quite see the necessity for the other expressions. With regard to using β for the attenuation constant, it is true that this was originated by Dr. Pupin; we have, however, been using, for what we think a

very good reason, α for the attenuation constant and β for the wave-length constant, because the real constant of telephonic transmission is the propagation constant, which is a complex quantity made up of two components—the attenuation constant, a real component, and the wave-length constant, an imaginary component, and it is better to write $\alpha + j\beta$ than $\beta + j\alpha$. From that point of view, if ever we are going to have a unit of the centibeta type—which I hope we shall not—it might perhaps be advisable to call it the centi-alpha. We express transmission results as equated results, and this method has been found universal in application. Mr. Whalley raised a point about the accuracy of speech testing. I do not hold by any means a brief for speech testing, and most certainly believe that in future we shall be able to do away with speech testing and substitute some method of testing which will eliminate the personal equation. But I cannot quite follow Mr. Whalley's argument. He says that as the gentlemen who went down to St. Margaret's Bay and made tests obtained very discrepant results, speech testing is therefore not satisfactory. That argument is almost the same as saying that the common battery telephone switchboard is of no value whatever, because even the most eminent electrical engineer who was introduced to its intricacies for the first time could not operate it. Speech testing requires a great deal of practice, and inexperienced persons get very discrepant results. Dr. Thompson has referred to his method of loading by parallel instead of series coils. Calculations have been made to demonstrate the impracticability of Dr. Thompson's method. I should like to show a slide that I have prepared in connection with this matter, dealing with some experiments that have just been carried out with parallel loading. In this particular case a 20-lb. conductor cable line, 20½ miles long, was loaded at 5-mile intervals with 0·2-henry loading coils on the Thompson method, and the attenuation at various frequencies was measured. Mr. Cohen.

This spacing gives an inductance of 1 henry per mile, and was based on the Pupin spacing formula, which, as Professor Fleming has pointed out, applies equally to the series and to the parallel-loading methods. The upper curve (A) is for the 20½ mile length of 20-lb. cable unloaded. Curve (B) shows the variation of attenuation for the same cable loaded on the Thompson method in the manner described above. It will be seen that the variation is even greater on the loaded line than on the unloaded line. The vertical dotted lines indicate frequency limits of 600 ∿ to 1,100 ∿ which are well within the normal speech range. The three ringed points against curve (B) were obtained by calculation using a formula devised by Mr. Shepherd. It will be seen that these points agree fairly well with the experimental results.

Before such a method as parallel loading is adopted, or even much money is spent on experimentally loading a line in this way, it will be necessary for Dr. Thompson to show that there is some method of putting these coils in parallel which will not give results

Mr. Cohen. of this sort. Below the curve (B) there is a third curve (C) for the same cable line loaded in series with an inductance of 0·5 henry per mile, and the variation in the attenuation constant between the two ranges of 600 and 1,100 is practically negligible. The dotted curve (D) put in is the curve obtained on the Anglo-French cable by measurement. I would like to ask what is wrong with that measurement. That cable is certainly not as bad as the measurement shows. I think the real reason is that there was a lot of unloaded cable in circuit, and therefore it does not show the variation of attenuation with frequency for the loaded cable.

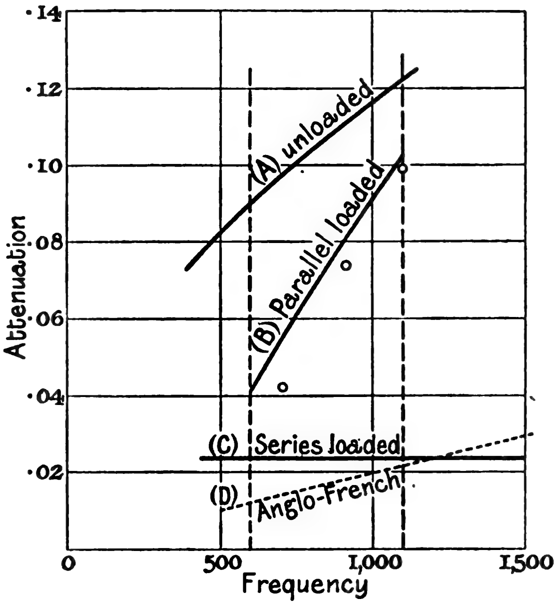


FIG. H.—Loaded Lines: Attenuation and Frequency.

Dr. Thompson has referred to the difficulty of making calculations with one single frequency fit in with actual speech results. Perhaps a definite statement on this point may be advantageous. A large number of elaborate tests have been carried out in many different countries to find whether there is any one single frequency which will give results when used both for calculating and for direct experiment which will be in agreement with those results obtained by actual speech measurements. The methods adopted in carrying out these experiments have varied considerably, and yet it is noteworthy that the results obtained are invariably in close agreement. One direct method has been to compare the attenuation values obtained by using various mono-frequencies with the actual speech values. Over here

we have in addition used a method of filtering the speech waves, and have also obtained the Fourier series for the average of a number of different telephonic speech waves, and several other distinct methods have been tried elsewhere, and the net result of all these experiments is to show conclusively that a single frequency of the order of 800 $\sim$ is the correct figure. This is as far as the volume factor of audition is concerned. With regard to the other factor embodied in audition, namely, articulation, the ratio of change of attenuation to change in frequency is known for various conditions of articulate telephonic transmission, and it is a comparatively simple matter to calculate or experimentally determine what this ratio is for any arrangement or device under investigation. Mr. Cohen.

Mr. J. G. HILL: As a member of the Post Office staff engaged on transmission work I wish to offer a few remarks. Dr. Fleming has told us that at a frequency of 750 the new cable obeys Pupin's sine law, but Dr. S. P. Thompson has pointed out that we have to consider many different frequencies in voice transmission. These remarks emphasise the fact that we have to consider not only volume of speech, but also its clearness. I think it is worth placing on record that this matter receives careful attention. Experiments have been made as follows to determine the point: Speech trials were made over a loaded cable, and it was found that when the coils were placed relatively near to each other and at equal distances, speech was quite clear. The coils were then spaced wider and wider apart and trials made at each step. It was then found that as the spacing was made greater speech became less distinct; at a given distance it was considered to be sufficiently clear, but when the spacing was then made greater it ceased to be clear enough. Knowing the distance apart at which the coils were spaced to give the required degree of clearness, the electrical constants of the circuit, and the amount of added inductance per mile, the wave-length at a given frequency was calculated and the number of coils per wave-length determined. This information enables us to design loaded cables with a predetermined clearness of speech. Mr. Whalley informs us that he considers the varying results obtained by Messrs. Judd, Kingsbury, Duddell, and Cooper, owing to the want of agreement, afford the best illustration we can have of the unreliability of speech tests for determining cable constants; but they do not appear to have been made for such a purpose, and no constant is given as being derived from them; they were expressions of opinion on the part of the gentlemen concerned. The taking of speech tests to determine β is in itself an art and requires considerable practice, but with skilled observers it is capable of giving fairly accurate results. I will ask you to look at Fig. I, which shows the result of a speech test. The ordinate shows the length of cable tested and the abscissa βl of the standard cable with which it was compared. Circles on the lower graph indicate points at which equal volumes of speech on the two circuits were obtained. It will be seen that six tests were taken, and that they all lie along a straight line. This makes the recorded results highly probable, Mr. Hill.

Mr. Hill. as it is known that the law is a straight line one, and this gives us a check on the results. In the case of the Anglo-French cable, voice tests and calculation agree very nearly; I refer to the tests conducted by the Department's officers. It is suggested that a complex wave obtained by a combination of alternators should replace the voice; but in view of the fact that the quality must also be determined, the voice cannot be dispensed with at present. Any successful method to compete with the voice must imitate it and should be more constant, but simple in its operation. Such a method is desirable, but not available. It was suggested by Mr. Whalley that it would be interesting if curves

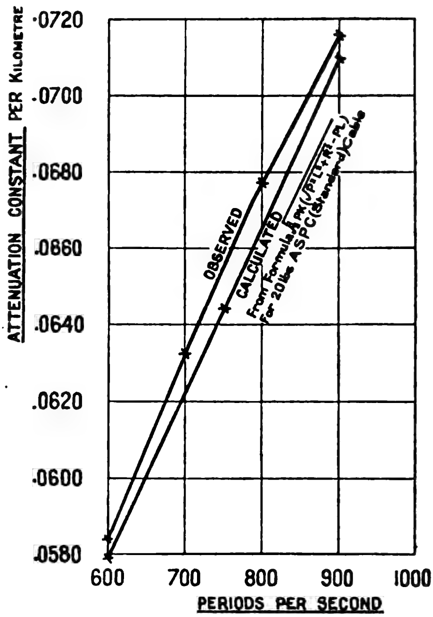


FIG. I.

showing the effect of frequency on unloaded cables could be given. A slide has been prepared showing calculated values for the standard cable and the measured result on an artificial cable made to imitate it, and at the same time permit of portability. It will be seen that the agreement is close, although some doubt was thrown on the accuracy of such a cable by Mr. Whalley. Mr. Sinclair, in referring to the question of duct space, seems to have great hopes that there will be plenty of room in the pipes, but I should like to call attention to the fact that the Post Office method is really to proportion the pipe to the cable. The pipes vary in diameter by half inches, and if we had half an inch to spare a wider spacing of air between the wires would be given so as to get the benefit of it and fill up the pipe.

Mr. J. E. KINGSBURY: I want to say a word in regard to the tests. I do not think it is becoming to make any remarks as to the efficiency of the people who made the tests, but I think we may agree that the tests were carefully made. I think we would also agree that the inferences drawn from those tests are not unreasonable. The human element cannot be eliminated from tests of speech. We may have some instrument which will help us in making tests, but we shall have to calibrate that instrument by means of human speech after all. It is for that reason that I want to draw attention to one point, and that is the figures used and the distances mentioned over which speech may be possible. I take it that the author intended those to be illustrative rather than to be regarded as of the nature of engineering specifications, for this reason, that until the time comes when we have a universal language (and I think these Channel cables will materially help to bring that time about) the cables will be largely used by people who have an imperfect knowledge of one another's language. We shall, therefore, need for such communication lines with a far wider margin than need be allowed where people are talking a language of which both have a perfect mastery. Without committing myself to distances or places, I can see that it might be feasible for two English correspondents to talk between London and Calcutta, and that it might not be feasible for natives of London and Astrakhan respectively to talk between those places. It follows, therefore, that we have nothing we can give away in dealing with these international problems. We want the best, and it is no use talking for one moment about the second best. I believe that in most cases it turns out, in the measure of £ s. d., that the best is the cheapest; but even if the best be the dearest, it must in such a case as this be taken advantage of. I mention that in order that there may be no question of being frightened by old experiences. The Indians have a proverb that a man who has been bitten by a serpent is frightened at a rope. A previous speaker has referred to the devils of the test-boxes. We should all bear in mind that we have acquired since the time referred to, quite a considerable experience in casting out devils. I do not want for one moment to go into detail on the merits of the two methods of adding inductance which have been referred to in the course of this discussion. Engineers will carefully weigh the respective merits and not be frightened at shadows.

Mr. Kingsbury.

Mr. ROLLO APPLEYARD (*communicated*): As my remarks will apply particularly to the tests described in the paper, they must necessarily be somewhat analytical, and I therefore desire to premise that they are not intended in any way to detract from the significance of the work that the Post Office and the contractors have accomplished, but that my object is to assist, if possible, in clearing up some of the difficulties that centre upon the attenuation constant. As regards the cable itself, I am convinced that the Post Office could not have embarked upon a policy more deserving of the gratitude of engineers, or better calculated to meet the needs of the public. And I am equally convinced

Mr. Appleyard.

Mr. Appleyard.

that—taking into account the fact that core of the type 160/300 was decided upon by the Post Office, and prescribed in their specification—the design and arrangement of the loading coils, from the electrical standpoint, by the contractors, could not be more closely in accord with what is now accepted as being the best theory and the best practice. Further, it is obvious that everything possible has been done by the contractors to design and to construct a cable that shall endure, to the lasting honour of the administrators and technical staff of the Post Office and of British cable makers generally. Those of us who were interested at the time that the construction of such a cable was mooted, in the autumn of 1908, feel that we owe a debt of gratitude to the author for the way in which he organised the initial investigations, and personally I am glad of this opportunity of recording my thanks to Mr. A. W. Martin for the zeal and courtesy with which he showed us his pioneer tests upon loaded circuits in London and Liverpool, and for the skilful assistance he gave to us in interpreting his results.

In considering the tests recorded in this paper, it is desirable to remember that, as engineers, the criterion always applied to our work is: Does it comply with the terms of the specification? In the present case the determining factor is the attenuation constant; and in conformity with the practice of the National Physical Laboratory and English custom, I propose to denote this by α, and not by β. The specification was to the effect that the volume of speech transmitted over a pair of wires in the completed and laid cable was to be "at least equal to that through one-seventh of the same length of standard cable not including terminal losses." The author tells us in his paper that the department stipulated in the specification that the attenuation constant should not exceed a certain value, and it is thus clear that the specified value of α was one-seventh of the attenuation constant of the standard cable. Hence—

$$\alpha_{\text{specified}} = 0{\cdot}1187/7 = 0{\cdot}01696 \text{ per N.M.}$$

Now, do the tests described in the paper prove that α for the cable, as constructed, was higher or lower than 0·01696? They appear to me to show that it is higher, and that consequently the terms of the specification are not fulfilled. There is such striking agreement between the "observed" and the "calculated" values recorded in Appendix IXA, as compared with the corresponding values given in Table A for continuous loading, that it is necessary to ask how the Appendix IXA. values of α were obtained. Let us deal first with the author's "calculated" value, 0·0166. Taking the data given in Appendix IXA, and putting them into the well-known formula reproduced at the beginning of Appendix X., α is seen to be, not 0·0166, but $\alpha_{\text{calculated}} = 0{\cdot}0214$. If the author had used the empirical formula at the top of page 324, and had assumed $S/K = 80$, he would have obtained $\alpha = 0{\cdot}0166$, but to justify the use of this value of S/K it is necessary to assure ourselves that in his case the ratio of leakance to

capacity is, in fact, 80. Appendix IXA. supplies an answer, for it is there seen that $S/K = 24/0{\cdot}138 = 174$, and, if this is true, the empirical formula must be abandoned. To test this, let us assume that $S/\omega K = 0{\cdot}018$, as found by Dr. Breisig for gutta percha, and as given on page 324. Then— Mr. Appleyard.

$$S/K = 2\pi \times 750 \times 0{\cdot}018 = 84{\cdot}8,$$

corresponding to a leakance—

$$S \doteq 84{\cdot}8 \times 0{\cdot}138 \times 10^{-6} = 11{\cdot}7 \text{ micro-mhos.}$$

In any case therefore the "calculated" value of a recorded by the author in Appendix IXA. is incorrect, and his value of the leakance is seriously in need of confirmation.

To assist matters, on the basis of the constants given by the author in Appendix IXA, I have calculated a as a function of the leakance for the new Channel cable, and the results are shown plotted in the accompanying curve, Fig. J. It is thus demonstrated that: (1) For a

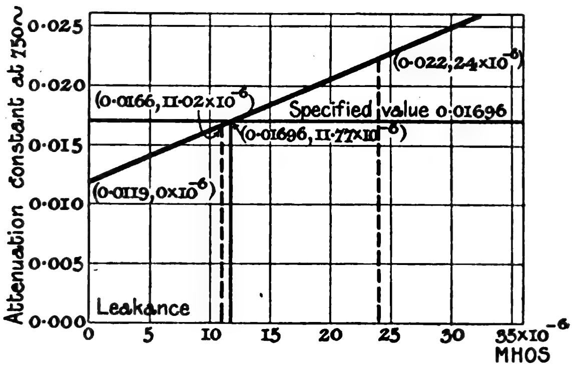


Fig. J.

leakance of 24 micro-mhos, a at 750 p.p.s. is $0{\cdot}022$; (2) to the value $a = 0{\cdot}0166$ given in the paper, corresponds a leakance of $11{\cdot}02$ micro-mhos; (3) unless the leakance is less than $11{\cdot}77$ micro-mhos, a at 750 p.p.s. cannot be less than the specified value.

Returning to Appendix IXA. it is important next to ascertain, if possible, how the author arrived at his "observed" value $a = 0{\cdot}0166$. The paper describes two kinds of tests from which a can for this purpose be deduced: (*a*) Speech tests; (*b*) current-measurement tests. It is convenient first to examine the speech test, remembering that—

a at 750 p.p.s. for standard cable	= 0·1187 per N.M.
a at 750 p.p.s. specified for loaded cable ...	= 0·01696 ,,
a at 750 p.p.s. for unloaded cable, given in Appendix IXA.	= 0·0766 ,,
Length of unloaded cable	= 41·7 N.M.

Mr. Appleyard.

On this basis the length of standard cable equivalent in speech value to the 41·7 N.M. of unloaded cable is—

$$\frac{0{\cdot}0766}{0{\cdot}1187} \times 41{\cdot}7 \times \frac{2029}{1760} = 31{\cdot}02 \text{ statute miles.}$$

Case 1.—Deducting 14 statute miles from this 31·02, gives 17·02 statute miles, or 14·76 N.M., as the length of standard cable equivalent to the 41·7 N.M. of loaded cable, and thus—

$$1 \text{ N.M. of loaded cable} = \frac{14{\cdot}76}{41{\cdot}7} = 0{\cdot}354 \text{ N.M. of standard,}$$

or—

$$a_{14} = \frac{14{\cdot}76}{41{\cdot}7} \times 0{\cdot}1187 = 0{\cdot}0420 \text{ per N.M.}$$

Case 2.—Deducting 24 statute miles from the 31·02, gives 7·02 statute miles, or 6·09 N.M., as the length of standard cable equivalent to the 41·7 N.M. of loaded cable ; and thus—

$$1 \text{ N.M. of loaded cable} = \frac{6{\cdot}09}{41{\cdot}7} = 0{\cdot}146 \text{ N.M. of standard,}$$

or—

$$a_{24} = \frac{6{\cdot}09}{41{\cdot}7} \times 0{\cdot}1187 = 0{\cdot}0173 \text{ per N.M.}$$

The discrepancy between the values of a deduced from the speech tests of the respective observers is thus so great that their observations must be regarded as worthless. To make matters worse, the figure 0·0766 given in Appendix IXA. and again in Table B, as the attenuation constant of the unloaded cable, is incorrect.

Taking the data given in that Appendix, the value of the attenuation constant works out as 0·0521. If a more favourable value of the leakance, say, 12×10^{-6}, be assumed, then the attenuation constant works out at slightly less, namely 0·0512. This value 0·0512 gives 20·74 as the equivalent in statute miles of standard cable, of the unloaded cable. Deducting 14 miles in the one case leaves 6·74 statute miles, or 5·85 N.M., as the equivalent of the loaded cable; and deducting 24 miles in the second case gives $-3{\cdot}26$ statute miles, or $-2{\cdot}83$ N.M., which is absurd. This value, 24 miles, is therefore out of the question, and the speech test as recorded by the author entirely fails as a guide to the quality of the cable. It may be pointed out that in Appendix IXA. the tables showing the conversion from N.M. to km. for the unloaded cable are in need of revision. As the speech tests are hopeless, attention may be turned to the current measurement tests given on page 323 ; and for consistency I shall continue to use a instead of β to represent the attenuation constant. The formula: $C_B = C_A e^{-ad}$ on page 323 is incomplete, as it does not take account of the reflections at the ends and junctions. A more exact formula, assuming that the

Mr. Appleyard.

receiving end of the artificial cable is short-circuited, as shown in the diagram on page 355, is—

$$\frac{C_A}{C_B} = \cosh a\,d + \left[\frac{Z_o'}{Z_o} \tanh a'\,d'\right] \sinh a\,d \quad . \quad . \quad (1).$$

Here—

$a = \alpha + j\beta$ for loaded cable.
$a' = \alpha' + j\beta'$ for artificial cable.
d = length of loaded cable.
d' = length of artificial cable at the receiving end.
Z_o = sending-end impedance of loaded cable.
Z_o' = sending-end impedance of artificial cable.

In this equation, if $a'\,d'$ is great, $\tanh a'\,d' = 1$. This presupposes a sufficient length of artificial cable added at the receiving end. In Fig. 5 artificial cable is shown added at the sending end, but this is superfluous, and it could more profitably have been added at the receiving end. Again, if in addition $Z_o' = Z_o$, that is to say, if the two cables are of similar type, so that there are no reflections at the point of junction, then the quantity within the square brackets is unity, and—

$$\frac{C_A}{C_B} = \cosh a\,d + \sinh a\,d = \epsilon^{a\,d} = \epsilon^{\alpha\,d}\underline{|\beta\,d}.$$

The hot-wire instrument ignores the phase difference, and the formula in that case becomes—

$$\frac{C_A \text{ effective}}{C_B \text{ effective}} = \epsilon^{\alpha\,d}, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

as used by the author. But in general this is only an approximation, and we must use equation (1) if an aocurate value of α is to be determined. Taking the better case, where a length of 15 miles of artificial cable is added at the receiving end, I have calculated that—

$$Z_o'/Z_o \tanh a'\,d' = 0{\cdot}7533\overline{|44^\circ\,32'},$$

which differs considerably from unity. Substituting this value in equation (1), an equation is found for $a\,d$; but as the phase difference between C_A and C^B was not observed by the author, we are unable to solve the equation for α. It is necessary therefore to arrive at α by a method of trial and error. That is to say, a probable value of α is put into equation (1), and the resulting value of C_A/C^B is then compared with the value given by experiment. This is shown in Fig. K. The curve connecting C_A/C_B with α cuts the horizontal through 1·927—the author's observed value of C $/C_B$—at $\alpha = 0{\cdot}02047$, and this is consequently the best value of α that can be derived from his test described on page 323.

Now compare this with the value of α derived from equation (2). Equation (2) gives, according to my calculation, $\alpha = 0{\cdot}01573$. But, according to the author's calculation, $\alpha = 0{\cdot}0152$. (The difference

Mr. Appleyard.

between 0·01573 and 0·0152 is, I think, to be accounted for by an error in the author's calculation.) There is a considerable difference between the more correct value 0·0205 from the equation (1) and the approximate value 0·0157 from equation (2). It is again to be observed that the 0·0205 is considerably greater than the specified value, 0·01696. It is extremely disappointing that no test has been made in the adopted scientific manner as used for example by di Pirro * in his tests upon telephone cables in Italy. That method is well known, and consists in measuring in the alternate-current bridge, the sending-end impedance, first with the distant end closed, and secondly with the distant end open. From the results, R, L, K, and S can be obtained. The general conclusion that must be drawn from these considerations

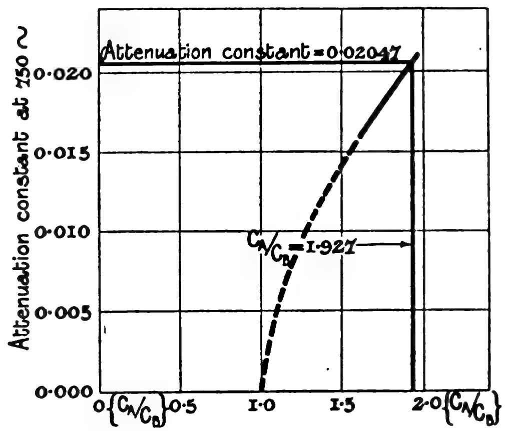


FIG. K.

is that there is no evidence whatever in the paper to show that the cable satisfies the specification as regards the attenuation constant. But it is clear that the contractors were left no margin. On page 316 it is stated that "it is not possible to predict with sufficient accuracy, by mathematical calculation, the results likely to be obtained by the 'continuous' loading, owing to the difficulty in attaching correct values to the electrical constants involved." It might with equal truth have been stated that, "owing to the difficulty in attaching correct values to the electrical constants involved," it is not possible to predict with sufficient accuracy, by mathematical calculation, the results likely to be obtained in respect to the capacity of a cable; for, owing to the irregular shape of the strand, it is extremely difficult to say what is the effective diameter of a strand. But it is common knowledge that this difficulty is entirely removed by making a test upon an experimental length of the given strand covered with the

* *Journal Télégraphique*, vol. 31, p. 25, 1907.

given dielectric. Similarly, it is possible to calculate the electrical constants of a continuously loaded core, if the values upon which they depend are found experimentally with sufficient accuracy. On page 318 the great discrepancy between the observed and the calculated values in Table A may be ascribed to incorrect values having been taken for these constants of the calculation. When these constants are properly chosen, sufficient accuracy for all practical purposes can be obtained. Change of permeability during winding is a well-known phenomenon, and it has been investigated by Dolezalek and Ebeling*; but in any case it is a simple matter to determine experimentally the inductance of a sample length independently of all formulæ—a few yards of sample conductor, without dielectric, is sufficient for this purpose. It is somewhat disconcerting to notice that in Appendix IXA. the capacity of the wire-whipped conductor core is represented as being 0·134, which is less than that of the core having a plain strand. As a matter of fact, the capacity for comparison in the case of the whipped conductor would be more like 0·185 microfarad. This mistake also vitiates Table B. **Mr. Appleyard.**

It is stated on page 321 that one reason for constructing the core of the 160/300 type is, that should the coils prove defective, they could be cut out and a cable obtained which would be a duplicate of the existing one. But a core of 107/150 type whipped with one layer of 8-mil wire, has a lower attenuation constant than an unloaded cable of 160/300 type, and its cost is naturally very considerably less—something like ½ for the dielectric alone. If the coil-loaded cable should prove unsatisfactory and the coils should have to be removed, the expense would be not merely the cost of the coils and their removal, but in addition the difference between the cost of a cable of 160/300 type and that of 107/150 type. There seems therefore to be a great field for the lighter type of whipped cable to replace all existing core of heavy unloaded type for speaking over the same distance.

Mr. J. F. COOTE (*communicated*): In connection with the cable to Ireland (page 313), the author has referred to the degradation of transmission which arises from joining circuits in parallel. The results obtained are confirmed by some experiments made a few years ago by the National Telephone Company. The first consisted in putting 12-mile lengths of 20-lb. cable conductors in parallel, and the equated lengths were found to be as follows:— **Mr. Coote.**

No. of 12-mile Lengths.	Equated Length.
1	12·0 standard miles.
2	15·3 „
3	16·5 „
4	18·6 „

that is to say, 4 pairs in parallel are actually 55 per cent. worse than a single pair. In another experiment 40 to 50 pairs of 20-lb. cable conductors about 6 miles long were placed in parallel and the trans-

* *Elektrotechnische Zeitschrift*, vol. 24, p. 770, 1903.

Mr. Coote. mission was so bad that speech was not articulate. Both these cables were ordinary dry-core underground cables.

By the usual formula for small gauge cables, the attenuation $\beta = \sqrt{1/2\, p\, K\, R}$ should, of course, remain constant, for the capacity is increased in the same proportion as the resistance is reduced, but when a large number of conductors are put in parallel in this way, the line impedance $\sqrt{R/p\, K}$ is reduced to a very small value, and the practical result is to put too much load on the induction coil. The above experiments also show why one of the claims made for multiple-twin cable was never realised. Although putting circuits in parallel, as a general rule, degrades transmission, there is one case to which I think attention should be drawn, where there is a gain and not a loss, viz., where parallel lines are used for the local line in central battery working. The reason for this is, of course, that the transmission allowance for the local line depends upon the feeding current through the transmitter, and by paralleling the lines a considerable increase of current may in many cases be obtained, with a consequent gain in the transmission. Experiments, which we have made in the Investigation Department of the National Telephone Company, have shown that in the case of parallel lines used in this way the allowance is governed simply by the ohmic resistance of the line, and that the effect of the increased capacity is negligible, at least up to 2 miles of standard cable, which will cover the majority of cases where it may be necessary to adopt this course.

In the tests made on the loaded cable at Woolwich (page 323), when artificial cables were inserted at the two ends to annul reflection losses, 10 S.M. being used in one test and 15 in the other, it appears that 10 S.M. was sufficient for the purpose, because the attenuation constant obtained was practically the same as with 15 S.M. When, however, the cable was tested after laying, it is stated on page 355 that it was found necessary to insert a length of rather more than 20 S.M. to prevent reflection. As the arrangement of circuit appears identical in the two cases, I should like to know to what the difference is due. 20 S.M. seems to me an excessive amount.

With reference to the formula for β given on page 324 it is stated that the value of the attenuation constant, indicated by a comparison with the artificial standard cable, requires the value of S/K to be 80. I should like to ask whether we are to understand this value to be generally applicable to gutta-percha cables, or only to the Anglo-French loaded cable, because I have tried to see how this constant would work out on the experimental loaded gutta-percha cable referred to on page 320, and using the data given there, I find β comes out at 0·0436 instead of 0·0427, which is given as the calculated value, *i.e.*, 4 per cent. greater than the experimental value, instead of 2 per cent. Now it happens that 80 is the constant which has been given by the Western Electric Company for calculating β for a loaded air-space cable, and was obtained by taking a large number of actual values of β on loaded lines by speech tests against standard cable, and seeing what constant, inserted in the formula, would give the same results. I am surprised to find that the

constant for gutta-percha cables is exactly the same as for dry-core cables. The value which must be given to the constant will depend, of course, on whether the alternating or direct-current value of the capacity is inserted in the formula. The alternating-current value is naturally the right one to use, but as the direct-current value can be obtained with far more accuracy than the alternating-current one, and the constant is only empirical, I think it would be preferable to use the direct-current value of the capacity. This was done, I believe, by the American Telephone and Telegraph Company, who originally got out the constant 80. The author has used the value 0·138 for the capacity, which is stated in the table in Appendix IXA. to be the alternating-current value at 750 ∿. I should like to know how this figure was obtained. For, in the specification on page 351, the maximum wire-to-earth capacity is given as 0·275 microfarad per N.M., and therefore the mutual capacity has a maximum value one-half of this, or 0·138, the same as given for the alternating-current value. Now the alternating-current value of the capacity is certainly less than the direct-current value, and the average ratio between them, as far as I can ascertain, is about 0·9, which would make the true alternating-current value certainly not more than 0·124. If we now insert this in the formula for β, and take β as 0·0166 we get a value of 94·5 for the constant instead of 80. Mr. Coote.

On page 340 the author has given the data of some foreign continuously loaded cables. At the meeting when the paper was read, one of the lantern slides gave particulars of the cables mentioned in the paper. I only caught a momentary glimpse of it, but I think at the end I saw another one, from Italy to Sicily. I should like to know if that is a recent cable, as I only know of the one laid in 1905, which had no iron wrapping. In addition to those given in the paper there is only one other of importance, the second Fehmern-Laaland cable, laid in 1907, which was a considerable improvement on the first, the attenuation constant being 0·013 per N.M. as against 0·0184 for the earlier one. Besides this, there are some short lengths between Korsor and Nyborg, and some on the coast of Iceland and between the Faro Islands. It seems likely that the present loaded Anglo-French cable will be a success in every respect, and consequently that continuous loading may not be again used for submarine cables. I therefore think, as this paper is historical, that it would be desirable to make the lists of continuously loaded cables complete, and I give such data as I have for those mentioned above.

In Appendix VII. the capacities are given as mutual, but are they not really the wire-to-earth figures? The values given, when turned into kilometre units, are double the mutual capacities given by Dr. Breisig,* which he states expressly in a footnote are for 1 km. loop. Again, to take the first cable, which is a gutta-percha one, if the mutual capacity is 0·324 microfarad per N.M., the wire-to-earth would be 0·628, and in the case of the last cable, also gutta-percha, it would be 1·00 microfarad per N.M., which are, I think, improbable values. In

* *Elektrotechnische Zeitschrift*, vol. 26, p. 385, 1905.

Mr. Coote. this connection I should like to mention that, in the National Telephone Company, we have long ago ceased to quote any single-wire values. They are merely a relic of the days when earth circuits were used; they are never wanted in practical calculations, and only serve to introduce confusion.

CONTINUOUSLY LOADED CABLES.

Mechanical Data.

Cable.	When Laid.	Length, N.M.	Number of Con-ductors.	Area of Copper, Square Inch.	Wrapping of Iron Wire (Mils).	Insulation Thickness in Inches.	Lead Sheath.
Fehmern-Laaland (No. 2)	1907	10·44	4	0·0112†	3 × 7·88	Air-space paper	Yes.
Korsor-Nyborg *	1906	10·32	—	—	—	Gutta percha 0·355	No.
Along coast of Iceland and between Faröe Islands	1907	—	—	0·0078	1 × 19·7	Gutta percha 0·315	No.

* This is made up of short lengths varying from 0·16 to 1·94 mile.
† The conductor of this cable is made up of a circular wire 84·7 mils diameter, surrounded by three trapezoidal wires 94·5 × 19·7 mils.

Electrical Data.

Cable.	Resistance per N.M. Loop.		Mutual Capacity per N.M.		Inductance per N.M. Loop, Millihenries.	Real Attenuation Constant (α) at 900 ∿ per N.M.
	Direct Current.	Alter-nating Current	Direct Current.	Alter-nating Current.		
Fehmern-Laaland (No. 2)	8·90 (at 59° F.)	—	0·087	0·077	18·2	0·0130
Korsor Nyborg ...	7·96 (at 68° F.)	8·64*	0·254	0·236	17·2	0·0211
Along coast of Iceland and between Faröe Islands	—	—	—	—	—	—

* This is at 765 ∿. The value at 1225 ∿ is 9·42 ohms per N.M.

In Appendix IXA. the figure 18·50 ohms for the steady resistance per N.M. is, I think, not quite correct, as the coils are given as 2·25 ohms each, and they are placed at intervals of 1 N.M. Adding this to 14·42 ohms, the value of the cable per N.M., we get 16·67 ohms for the total resistance. In the last paragraph of the paper I do not understand what is meant by "β per second." I take it to be a misprint for "β per N.M." Also, why is the frequency of 800 mentioned in connection with the speech test? The value for β so obtained is an

experimental one, and does not depend upon any assumption as to what single frequency most nearly represents speech. Why is β given as 0·0169 instead of 0·0166 as in Appendix IX.A? Is this intended to be some correction based upon a change of frequency from 750 to 800? If so, I do not see how it can be done for a speech-test value. Mr. Coote.

Mr. L. B. TURNER (Post Office) (*communicated*): In that part of his paper dealing with continuously loaded cables, the author has shown how unsuccessful have been the attempts to pre-determine the efficiency by mathematical calculation; and I should like to make a few remarks bearing on this point. Before attempting to account for the error of the calculated results referred to, we must understand how much is meant by such terms as "calculation" and "pre-determination of results" when used in the present connection. Sir John Gavey has spoken of a continuously loaded cable designed by him, in which the calculated attenuation is very nearly equal to the observed; and he suggests that this superior agreement is due to the use of iron strip annealed after the wrapping, instead of wire left unannealed. But while Sir John Gavey is to be congratulated on having produced, probably, the best continuously loaded cable that has yet been made, it cannot be conceded that this cable marks any advance in the accurate pre-determination of efficiency. The β of this cable was only calculated from its inductance and resistance as measured, and this is precisely the calculation we are making every day for coil-loaded cables, with the pronounced success that Major O'Meara has indicated. We measure the inductance, the resistance, and the capacity of loop and loading coils, and then calculate β with the aid of the Heaviside formula. And, as Dr. Fleming has reminded us, this formula belongs to the continuously loaded cable, and is only applicable to coil loading at all in so far as the Pupin ratio— Mr. Turner.

$$\sin\frac{\theta}{2}\Big/\frac{\theta}{2}$$

may be equated to unity. There are three degrees of completeness of calculation for the β of a continuously loaded cable; and of these the one just considered is the most empirical. At the other extreme is Professor's Larsen's work, whose formulæ are summarised in Appendix VIII. of the paper. Larsen takes, as experimental data, only the permeability and the specific resistance of the iron wrapping, and from these he calculates the inductance of the loop and the eddy-current loss in the iron. It is the figures yielded by these very fundamental calculations which have proved so unsatisfactory. The intermediate procedure, not quite so radical as Larsen's, is to make a preliminary test of a sample of the iron in order to find the permeability and the losses experimentally.

Now as to the cause of the discrepancy. I believe that it lies in the rather obscure magnetic resistance offered by a joint in an iron circuit, a resistance apart from, and in addition to, the resistance of any air-gap separating the two iron surfaces. This was first noted by Professor

Mr. Turner. J. J. Thomson in 1887, and is discussed by Professor Ewing in his book on "Magnetic Induction." Ewing made experiments to determine the length of the air-gap equivalent to a junction in the iron of the circuit. His tests embraced a considerable range of flux density, but unfortunately for our present purpose, the density was always high; so that until experiments have been made at the low densities which here concern us, it is only possible to make a more or less rough estimate of the effect of a junction. This effect, however, is probably large, and it finds no place in Larsen's formulæ. The a in the equations of Appendix VIII. allows for the air-gap necessarily crossed by a circular

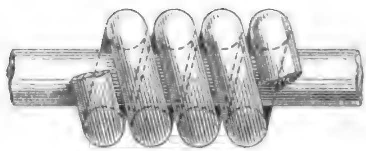


FIG. L.

flux traversing a helical wire wrapping, but the independent junction resistance is not expressed. Dr. Breisig, in his new book "Theoretische Telegraphie," slightly modifies Larsen's expression for a, but he also omits to take account of junction resistance.

That this resistance must not be overlooked, and that, when duly allowed for, satisfactory calculations can probably be made, is evidenced by the following figures. The cable tested was one whose conductors were loaded with a single layer of iron strip, annealed after wrapping. Its inductance and resistance at 820 p.p.s. were measured, and, from tests made on a sample of the iron, the permeability and the iron losses were independently calculated. Measured and calculated values for the cable were then as follows:—

	L.	R.	β.
Measured	17	5·8 (+ 17·6)	0·021
Calculated	20	7·3 (+ 17·6)	0·021

Considering the absence of exact information as to junction resistance at low flux densities, the agreement in the values for L and R is satisfactory. The equality of the two values of β is of course an accident, due to the discrepancies in L and R neutralising each other. If the junction resistance had been neglected, the calculated inductance would have been some 30 per cent. higher. In the cable of Appendix IX. of the paper the neglected junction resistance is much more important even than this.

Mr. Turner.

Turning now to the proper value to be attached to μ in the calculations, Dr. Fleming has spoken of the difficulty of measuring permeability with the small high-frequency forces to which the iron wrapping of a continuously loaded cable is subject. Dr. Fleming suggested that this difficulty may be responsible for the erroneous calculations of β, and he mentioned his very interesting method for determining μ as a factor in the observed high-frequency resistance of iron wire. Perhaps hidden difficulties are yet to be met, but hitherto I have found no objection to the ordinary ring form of core for determining the permeability of the iron. My test-rings have been about 8 cm. in diameter, with an iron cross-section of about $\frac{1}{3}$ sq. cm., and wound with a single layer of No. 21 gauge copper wire. The measured inductance of such a ring gives the required permeability of the core, while the difference between its resistances under the appropriate alternating current and under direct current—which difference I will denote by r_c—allows the core loss, and thence the effective resistance of the loaded cable to be determined. In these rings I have been surprised to observe that with increase of current r_c increases more rapidly than the square of the inductance or permeability. A pure eddy loss, being proportional to B^2, would make r_c/μ^2 constant; and the observed increase of r_c/μ^2 indicates a core loss rising more rapidly than the square of B. This, I think, can only be attributed to hysteresis; although, at large forces, hysteresis loss is roughly proportional to the 1·6th power of B, and is commonly supposed to vanish at very low forces.* Similar rise in resistance has been observed in loading coils at the Post Office, and in a paper by Dr. Ebeling I see it also mentioned in connection with the German loading coils.

If this hysteresis loss is present, one would anticipate great difficulty in allowing for it in Dr. Fleming's resistance method of measuring μ. For if μ varies with the frequency, we cannot assume that the hysteresis loss per cycle is independent of the frequency, and consequently the ordinary method of separating hysteresis and eddy losses fails.

In the absence of other published information, the following figures may be of interest in showing the kind of permeability values to be

ANNEALED IRON WIRE. $H = 0{\cdot}01$.

Test.	μ.
1315 ∾	144 (91)
776 ∾	154 (99)
Ballistic	158

* At infinitely low values of H, if μ is to remain finite, it can easily be shown on *a priori* grounds that any remaining hysteresis loss must vary more rapidly than B^2.

Mr. Turner. reckoned with in the iron of a continuously loaded cable. The values of μ enclosed in brackets refer to the wire after being overstrained, as by wrapping round the copper conductor.

Mr. Wilkinson. Mr. H. D. WILKINSON (*communicated*): This paper marks a very important advance in the application of inductance to submarine cables for telephonic transmission. The attenuation of the impulses and the distortion on long lines at low frequencies have long been familiar to those who have had to do with telegraph submarine cables—in fact, years before telephoning through them was thought of. The distortions of impulses have been known to be due to the rush of charge into the dielectric and the incomplete discharge between successive impulses. In telegraph cables this has been corrected to a very satisfactory extent by electrical and mechanical curbing, the magnetic shunt, inductance inserted in the line, and other shore devices suitable to the low frequency and the mechanical nature of the transmission. In telephony the impulses are not started direct from a primary source, but are induced and subject to modification of wave-form in the transmitter.

The Duddell oscillograph has revealed the character and frequency of these impulses, and mathematical treatment based on Heaviside's papers has received an immense degree of elucidation in the hands of Pupin, Kennelly, Hayes, Campbell, Kempe, and other investigators, which has enabled the characteristics of the line and action on the impulses to be separately studied. The most important outcome has been the addition of inductance along the line to counteract the distortion effect of capacity. The trials carried out by the engineers of the Post Office, the National Telephone Company, and Continental undertakings during the last ten years have given valuable experience of both continuous and spaced loading.

The author shows in Tables A and B the great increase in speaking efficiency produced by continuous loading by which the attenuation constant can be reduced 50 to 70 per cent. as compared with an unloaded cable, also the still further gain of 10 to 15 per cent. by spaced loading. He has shown in Appendix VI.B that for equal telephonic efficiency a spaced loaded cable costs materially less than a continuously loaded one. Hence there is only one conclusion—that in the present state of the art, for least cost and maximum efficiency, spaced loading was the right thing to apply to the new telephone cable. Mechanically, however, spaced loading in a submarine cable involves greater risk in the usual operations; the cable is also less simple to manufacture and handle than a continuously loaded cable of uniform overall dimensions.

The insertion of inductance coils in aerial lines at poles or in underground lines at test-boxes is a comparatively simple matter, but it is not so simple to insert isolated coils in a submarine cable so that all exigencies attending cable operations can be satisfactorily met. We have it in the paper that Continental engineers have kept to continuous loading, possibly reckoning the additional efficiency of spaced loading not worth the mechanical difficulty and risks involved.

The contractors for the new cable—Messrs. Siemens—are to be warmly congratulated on the design of the new Channel cable. Without any data or suggestion of the electrical and magnetic dimensions of the coils or their spacing in the specification, they have succeeded in a design correctly complying with the requirements as regards attenuation. They have also developed a very neat way of fitting-in the coils in the cable and the working-in of a second layer of sheathing wires to cover the bulge. Moreover, they had to undertake the laying with full responsibility, and carried everything out to a successful issue. This cable will probably be the approved type for future telephone cables in this and greater depths. It is not likely that lead-sheathed paper cables will again be laid in any depths exceeding 100 fathoms, notwithstanding the advantage of lower capacity and lower cost of dielectric. Deformation took place in the Lake Constance cable at the test pressure necessary to secure a proper factor of safety for 138 fathoms depth, and this contingency had to be provided for by a steel-wire spiral under the lead sheath. This considerably reduced the flexibility of the cable, and a very elaborate gear was provided for laying. Mr. Wilkinson.

The new telephone cable, from the description in the paper, required careful nursing in laying, but the contractors anticipate no difficulty in repairing operations. The localisation of breaks and faults and the picking up and re-insulation of the coil portions will, at any rate, be novel and of great interest to those fortunate enough to be engaged on the work. Judging by the number of positions where previous cables have been damaged and repaired, as shown on the chart in Fig. 17, there should be no lack of opportunity in the near future for proving the facility with which repairs can be carried out.

There is one point in the earlier part of the paper which I do not think has been touched upon, namely, the comparative trials on page 313 between two ordinary telegraph cables and an air-space telephone cable 60 miles long between Wales and Ireland. It would appear from the particulars given of these cables in the paper that the diagonally opposite pairs of conductors in the air-spaced cable were spaced 30 per cent. nearer to each other than those in the telegraph cables with which the comparison was made, and 50 per cent. nearer than the conductors in the 1891 Paris cable. The electromagnetic induction between pairs producing overhearing would, therefore, be largely due to the greater proximity of the conductors in the air-space cable and not wholly to want of symmetry in manufacture as suggested on page 314. The importance of separation between conductors as one factor in increasing the range is laid down in recommendation (*a*), page 315, and although this consideration was kept in view as regards subsequent cables it does not appear to have received the attention it deserved in the dimensions of the air-space cable. The length in this case being three times that of the Paris cable, the separation of the conductors should have been greater, whereas the actual separation was very much less. It hardly appears to me, therefore, that a fair case is made out for the complete abandonment of this type.

Mr. Wilkinson. In the Willoughby Smith and Granville air-space cable the gutta percha is moulded round the conductors in the form of an arch so as to give great mechanical strength suitable for laying in depths up to 250 fathoms. Either continuous or spaced loading could be adapted to this design of cable. The reduction of capacity due to the air space between conductors would mean that a less degree of loading would be required for the same speaking effect, and it might, therefore, work out that continuous loading in this cable would give very nearly the maximum efficiency. If so, the advantage of a perfectly uniform exterior would be secured. On the other hand, spaced loading, if employed, could be carried out at longer intervals owing to the lower capacity and lower dielectric conductance, and if the coils were placed as in the Romanshorn cable, but with thinner and more elongated cores, they could be stowed away in the air-space with very little increase in the over-all diameter.

Mr. Rayner. Mr. E. H. RAYNER (*communicated*): The difficulties of submarine telephony are well indicated by the figures on page 355, where measurements made show that at a frequency of 1,700, three-quarters of the current put into one end of a 40-knot cable disappears, and only one-quarter arrives at the other end. At a lower frequency, about 750, nearly half the current is lost. A very minute and quite inappreciable portion of this loss may be put down to true insulation resistance leakage; and a second portion to apparent leakage caused by dielectric losses due to the use of alternating potentials. Considering a concentric cable as a condenser which is subjected to an alternating difference of potential, there is always some loss of energy at each alternation. The dielectric does not give out on discharge quite so much energy as is required to charge it. In consequence, the losses in a cable appear to be much greater when subjected to alternating potentials than when subjected to continuous potentials. The energy loss simulates a lowering of the insulation resistance, which becomes more important as the frequency is raised. Thinking that some experimental results on this subject would be of interest, and possibly of some value, I have attempted to measure the energy loss in a short length of gutta percha covered wire, with the idea of calculating the loss in a longer length of similar cable at about telephonic voltage and frequency. Such calculations depend on the assumption that the energy loss varies as the square of the voltage. In the calculation below I have assumed that this holds over a range from 1 volt to 1,000 volts or more. It is known that the relation holds over a wide range of voltages, and the experiments below indicate that it holds over a range of 1,000 to 4,000 volts in the case of the cable experimented on. The fact that the power factor is about 4·3 per cent., which is but little higher, I believe, than is usually found for gutta percha at lower voltages, shows that the assumption is very largely justified, and the results ought to give a good idea of the order of magnitude of the loss at small voltages. The cable tested was 7·3 metres in length. It was 4·5 mm. external diameter, and the conductor was 1·25 mm. in

diameter. It was placed in water, and the energy required to charge it was measured by an electrostatic wattmeter. This instrument was designed for the measurement of such insulation losses at several thousand volts, and, as at present arranged, it is not sufficiently sensitive to measure small quantities of energy at lower voltages. The frequency was about 50, and the temperature 9·5° C. In the following table the watt measurements have been divided by the square of the kilovolts, which should give a figure that is the same for all voltages if the square law above mentioned holds. This, it will be seen, is the case to the accuracy attainable by these measurements. The charging current is proportional to the voltage to a similar degree of accuracy :— Mr. Rayner.

CABLE : 7·3 metres of 1·25 mm. conductor covered with gutta percha to 4·5 mm. Temperature, 9·5° C. Frequency, 50.

Volts.	Watts.	$\frac{\text{Watts}}{(\text{Kilovolts})^2}$	Amperes.	Volt-amperes.	Power Factor.
					Per Cent.
4,000	0·250	0·0156	0·001460	5·84	4·25
3,000	0·142	0·0158	0·001110	3·33	4·26
2,000	0·062	0·0155	0·000726	1·45	4·27
1,000	0·016	0·0160	0·000369	0·37	4·32

Taking, for example, the figures obtained at 2,000 volts, the watts per metre are 0·0085. At 1 volt instead of 2,000 this would be $0·0085/2,000^2 = 0·002125 \times 10^{-6}$. For a length of 40 knots (=46 km.) the loss would be 0·000098 watt at 50 frequency. As this loss is proportional to the frequency, it would at, say, 750, be 15 times as much, or 0·00147 watt. This small quantity of energy absorbed by the gutta percha when subjected to an alternating difference of potential of 1 volt does not appear to be of great importance, but it is, I believe, a fairly large amount in telephone engineering, and I shall be interested to hear what the author has to say on the subject, and whether he can supply any figures of this source of loss in telephone cables. If simultaneous watt measurements could be made at the two ends of a telephone cable transmitting a musical note at a known voltage and frequency, the difference of the readings of the two instruments would give the total loss of energy in the cable. Subtracting from this the C^2R loss, allowing for attenuation, the remainder ought to give the energy loss in the insulating material, which is only to a very small extent true resistance loss. The difficulties of measuring power at such low voltages are very great; it will be interesting to hear what figures are available on the subject. If they support the value obtained

Mr. Rayner. above, it would confirm the square law, upon which the calculation is based, over a wide range of voltages: future cable dielectric losses could be measured at high voltages; and as the facility of measurement increases very quickly with the voltage which can be used, the measurements become comparatively simple. It seems that except as a water-tight external covering, the use of gutta percha as a dielectric for telephone cables must give way to some material of smaller dielectric constant, and of possibly smaller effective leakance. In any case, the use of it in the space between the two wires of a circuit is to be restricted as far as possible, and it is unfortunate that paper loses its insulating property when used with an outer layer of gutta percha under water. Something on the lines of the air-core cable (Fig. 15) with just sufficient gutta percha to make a satisfactory covering for the wires might be practicable; and to prevent the failure of this type of cable from a telephone point of view, due apparently to loss of symmetry, it might be made solid in the middle with some material such as dry wood in lengths of about 2 in., if it is possible to impregnate it with some such material as paraffin wax to prevent the absorption which occurs with paper, grooved to fit the shape of the wires with their covering. If allowed to become damp the loop capacity would rise very rapidly.

Since writing the above I have gone further into the matter, and the experiments led to the unexpected result that the temperature coefficient of energy loss at 50 $\sim$ was negative, the loss falling off as the temperature rises at a rate of rather more than 1 per cent. per degree Centigrade. The whole series of experiments seemed to be of such interest that Mr. Campbell has kindly obtained results for me on the same piece of cable by entirely different means. He has employed Rowland's modification of Carey Foster's method, using about 10 volts and a frequency of 800. The resulting power factor comes out at about 5 per cent., in contrast with 4·3 per cent. at 4,000 volts and 50 $\sim$, and he also confirms the temperature coefficient. I am not sure of the relative importance of these effects compared with others as regards the difficulties of submarine telephony; but perhaps the author can give values found at the usual test temperature of 75° F. (24° C.), and the results of similar tests at ordinary sea temperatures.

Mr. Shepherd. Mr. G. M. SHEPHERD (*communicated*): In regard to the formulæ given in Appendix X., I would like to ask whether the constants in (1) are for the single-wire circuit. Although the expression of resistance in terms of one wire may be a convenience to manufacturers, it would appear that to deal with the other three constants in a similar manner may lead one into considerable difficulties, since the ratios, for instance, between loop and earth capacities, or loop and single-wire inductances, are by no means invariable. We are still in a transition stage as regards cable testing, but sooner or later the manufacturer will have to work in mutual values, just as the telephone engineer must think in them.

Mr. Shepherd.

Turning to the short formula given for attenuation—

$$\beta = \frac{r + 0{\cdot}14\,l}{63{\cdot}2}\sqrt{\frac{K}{l}},$$

which is stated to apply to the special case of *l* millihenries greater than *r* ohms, I think this limitation is rather too severe, as the type of formula—

$$\beta = \tfrac{1}{2}\,R\sqrt{K/L}$$

is known to apply quite closely even when the R is considerably larger than the L in millihenries. A better criterion is probably the ratio p L/R, where p is taken to be, say, 5,000, and L is in henries. If p L/R is 3 and upwards, then the above shortened forms are accurate enough for all practical purposes.

Now in regard to Mr. Kempe's expression for the most efficient loading, there is another factor which has an important bearing upon the loading limit, more particularly in the case of local junction lines; that is the terminal loss. The following formula—

$$m = \frac{l}{a} f(L) + F(L),$$

is a general statement of the value in miles of standard cable for a loaded cable of length *l*, where *a* is the attenuation constant of standard cable, and f(L), F (L) are functions of L representing the attenuation of the loaded circuit and the terminal loss respectively. The latter function depends upon the form of the loss curve for any particular terminal condition. As an example, take the case of a loaded cable between two C.B. exchanges having subscribers' lines equivalent to, say, 2 miles of 20-lb. cable. The above formula becomes—

$$m = 9{\cdot}45\,l\left(\frac{R}{2} + \frac{127\,L}{2}\right)\sqrt{\frac{K}{L}} + 10{\cdot}75\sqrt{L},$$

and for a minimum, L, the limiting inductance per mile is given by—

$$L = 0{\cdot}0022\,l\,R/(0{\cdot}279\,l + 21{\cdot}5),$$

if K is 0·054 microfarad per mile. Thus if the line is 10 miles long and conductor resistance = 44 ohms per loop mile, the limit is 0·04 henry as against about 0·35 henry if no terminal effect required consideration. A set of empirical formulæ like this for the terminal conditions usually met in practice will save much cut-and-try work.

I would like to add a few remarks respecting Dr. Thompson's advocacy of the inductive leak method of loading. Dr. Thompson is sceptical of the so-called mean speech frequency, and its use in transmission calculations, though, by the way, he suggests the employment of such a figure in his 1891 specification. Now, if one considers a compensated cable on the Thompson principle, and determines the

Mr. Shepherd.

attenuation constant for a number of frequencies, some rather curious results may be obtained. Let us assume that by means of suitably spaced bridged inductances a value L′ per mile is given to the line: also for simplicity let the coils have negligible effective resistance, and the line negligible leakance. Then β is given by—

$$\beta = \sqrt{\frac{p}{2}\left(K - \frac{1}{L^1 p^2}\right)\sqrt{R^2 + p^2 L^2} - p L}.$$

Now let—

$$\left.\begin{array}{ll} L' = 0{\cdot}5 & \text{henry per mile} \\ L = 0{\cdot}0017 & \text{,,} \quad \text{,,} \\ K = 0{\cdot}12 & \text{mfd.} \quad \text{,,} \\ R = 12{\cdot}5 & \text{ohms} \quad \text{,,} \end{array}\right\} \text{Unloaded Paris cable.}$$

∾.	β of Thompson Line.	β of Unloaded Line.
660	0·00713	0·0425
1,000	0·03530	0·0466

If the above figures mean anything, the variation in attenuation over a region rich in distinctive telephonic tones may amount to several hundred per cent., as against 10 per cent. in the case of the unloaded cable. Then, again, considering the characteristic impedance of the lines, differences of the same order are found, viz., a change of some hundreds per cent. for the Thompson line, against about 15 per cent. for the unloaded cable. Loading of this sort is therefore likely to lead to distortion of a remarkable kind, though it might be well adapted to single-frequency telegraphy by alternating currents. Dr. Thompson pleads for a practical trial of his system. This would no doubt be a matter of much interest, but until its inventor translates his faith into plain arithmetic, as Pupin did, series loading is likely to hold the field.

Mr. Bennett.

Mr. A. R. BENNETT (*communicated*): I see that doubt exists as to when Mr. Oliver Heaviside's investigations were first translated into practical action. Mr. Heaviside discussed two methods of improving the efficiency of long-distance lines: (1) By leaks (which was not new); (2) by reducing resistance and increasing inductance. The former plan I tested practically in 1888 when erecting the first trunk lines through Fife for the purpose of bringing Dundee and Aberdeen into communication with the Scottish southern systems. The line from Stirling to Dunfermline, and thence on to Burntisland, was furnished with weather-proof shunt coils at every half mile, this section being approximately midway between Edinburgh and Glasgow and Dundee. The line spoke quite well over the longest distances which could then be brought into circuit, about 200 miles roughly, but not appreciably better than it did on a wet day without the shunts. It was, of course, an

Mr. Bennett.

early observation—anterior to Mr. Heaviside's work—that long lines spoke better in damp than in dry weather, the uniform leakage due to wet insulators being decidedly better than very high insulation, at least for the distances then practised. It chanced that Lord Kelvin, then Sir William Thomson, asked me soon after the coils were fitted if anything had been done in this direction, and was delighted and very much interested on hearing about the Stirling-Dunfermline trunk, about which he made minute inquiries. He then spoke of the inductance theory, mentioning Mr. Heaviside's name with much appreciation, although I am not sure that the paper on the subject had then appeared in print. I had, however, previously heard of the theory in some way. Lord Kelvin said that probably a practicable way to apply the inductance method would be to insert coils at intervals along a line. If I am not mistaken, Mr. Heaviside did not himself suggest loading lines with coils till the first volume of "Electro-Magnetic Theory" appeared in 1893. The copper wire with which the trunks were run provided speaking good enough for existing purposes, and I did not think it worth while, especially in view of the negative results obtained from the shunts, to trouble about inserting coils on any of the lines. But Mr. Heaviside's labours did save the National Telephone Company a little money on one occasion by preserving in use an iron wire that would otherwise have been scrapped. Selkirk was originally joined to Galashiels by a single No. 11 galvanised iron junction wire about 6 or 7 miles long. When the copper metallic circuit trunks were extended from Edinburgh to Galashiels and Hawick in 1889 it became necessary to turn this into a metallic circuit in order that Selkirk might use the trunks to best advantage. This was done by running a No. 14 copper alongside, and crossing it every half mile with, the iron, so that the loop was half copper and half iron in alternate half-mile lengths. Of course the iron brought resistance with it as well as inductance, but mixing it with copper enabled it to be used over the longest lengths then available, which a loop composed wholly of No. 11 iron could not have been without notable disadvantage to the speaking. Both this line and the shunted Dunfermline trunk were still at work when I resigned from the National Telephone Company in 1890. I understand that the foreman, Mr. A. Maclean, who erected the shunts, is still with the Company, and will surely recollect them. The Selkirk compromise, I learnt two or three years ago, was well remembered by Mr. C. M. Gardner, who was local manager in the Galashiels district in 1889. The sale of the trunks to the Post Office, where inductance for telephone lines was not then believed in, put a stop to such experiments; but I think I have said enough to show that Heaviside was not, in the early days, ignored entirely by engineers of his own nationality.

Mr. Bright.

Mr. Charles Bright, F.R.S.E. (*communicated*): At a time when this subject was more or less in its infancy, I had occasion to collect particulars of various suggested telephone cables for the purposes of a certain book. In this may be found the first published descriptions of (*a*) Dr. Thompson's proposed cable with

Mr. Bright. distributed shunt inductance; (*b*) Mr. (now Sir) W. H. Preece's twin conductor cable—with metallic circuit; and (*c*) Messrs. Willoughby S. Smith and W. P. Granville's air-space cable.* It was then in (1898) a moot point whether any of the developments of Mr. Oliver Heaviside's and Professor Pupin's mathematical enunciations would meet practical requirements. Whether or no these devices have been given a sufficiently full trial under favourable conditions—say for underground purposes—I am not in a position to state. However that may be, it is only to-day that we can be said to have achieved—by an entirely different method—a really satisfactory solution to the problem of employing self-inductance for neutralising the unfavourable electrostatic capacity effects of a long-distance telephone circuit. Whilst yet another method—that of continuous loading—may be a more correct method theoretically, the experimental results so far obtained by the Post Office appear to favour distributed coil loading (with its obvious advantages in the way of mechanical simplicity)—as adopted in the recently laid Government cable—if only for financial reasons. It seemed at one time as though inductance coils could never be made to form part of a submarine cable—owing to the "blobs" involved being a source of serious difficulty in laying and repairing operations—but all these objections have been successfully coped with; and, as a pioneering work, the result can but be a great source of satisfaction to those concerned, especially to Mr. Dieselhorst, the more so as the line was made and laid across the English Channel without a single hitch. Any one inspecting the device cannot fail to be impressed with its workmanlike and lasting character.

When witnessing the cable being shipped on board Messrs. Siemens' Telegraph ship *Faraday*, I watched with much interest—not unmingled with misgivings—the passage of that part containing one of the loading coils as it passed over a pulley. The special arrangement of fleeting knives is, of course, highly interesting to the cable engineer. Probably due to a slight clerical slip, a passage in the author's paper seems to imply that the provision of fleeting knives for the paying-out brake drum was either novel or unusual; but I need scarcely remark that fleeting knives have been invariably employed in cable work for almost as long as cables have been laid.† The special precautions adopted on the *Faraday* were, however, entirely original, and have, I fancy, proved highly effective for meeting the exigencies of the case.

Mr. Alexander Siemens has already called attention to the real significance of the word "knot," and has pleaded for "naut" as the proper foreshortening of "nautical mile." I would, however, venture to plead for "N.M.," the fact being that "naut" both frequently sounds like "knot," and is often so recorded by the printer. To my

* "Submarine Telegraphs: their History, Construction, and Working," pp. 685–693.

† Previously used in colliery work, they were first adapted to the fore and aft of a cable drum by the late Mr. R. S. Newall when fitting up the old (original) *Monarch* for laying some of the earliest cables to the Continent.

mind, it is only in instances of anything in the nature of a table that any foreshortening should be necessary. Mr. Bright.

Professor G. W. O. Howe (*communicated*): At the top of page 348 the author makes the following statement: "It may be remarked that the equation $\beta = 0{\cdot}01183 \sqrt{kr}$ indicates that a properly-loaded cable, in relation to telephonic efficiency, does not follow a "kr" but a $\sqrt{kr}$" law, and it also follows that the efficiency is inversely proportional to the length and not to the square of the length." It is not very clear what is meant here by telephonic efficiency, nor how it follows that the efficiency, however defined, is inversely proportional to the length. Both the current and the voltage along the line fall off according to the exponential expression $e^{-\beta l}$, and although βl is proportional to the length it is not obvious how the efficiency can be shown to be inversely proportional to the length. As the author says, a properly loaded cable follows a $\sqrt{kr}$ law. Is this not also true of an improperly loaded cable? It appears from what has immediately preceded this statement that proper loading is that which gives the minimum value to β; if, however, the loading have other than the theoretically correct value, it will alter the figure 0·01183, but will not alter the $\sqrt{kr}$. Although not expressly stated, the statement, as it stands, might easily lead one to imagine that it was the loading of the cable which had, in some mysterious way, lifted it out of the sphere of the "kr" law into that of the "$\sqrt{kr}$" law. Now, the "kr" law has nothing to do with the question of efficiency, except in the special sense in which the working speed of a submarine cable may be taken as a measure of its commercial efficiency. To make this quite clear, let us assume that the cable is quite unloaded so that its inductance is negligibly small. If we also neglect the leakage we have the case originally solved by Kelvin in his classical researches on the subject. Putting $L=0$, and $S=0$ in the opening formula of Appendix X., we get— Professor Howe.

$$\beta = \sqrt{\tfrac{1}{2}\sqrt{p^2 K^2 R^2}} = \sqrt{\frac{p K R}{2}}\,.$$

Here in the absolutely unloaded cable we have still the "$\sqrt{kr}$" law. In submarine telegraphy, however, we are concerned with the frequency p at which we can work, for on this depends the number of words per minute, *i.e.*, the earning capacity of the cable. As the value of β is fixed by the sensibility of the recorder, the value of p K R is also fixed. Hence the frequency p, and therefore the possible speed of working, are inversely proportional to K R. We see therefore that this is not a matter of proper loading or even of loading at all.

Turning now to the body of the paper, I find no mention whatever of the relative phase-displacement of the various harmonics. Is one right in assuming that telephone engineers depend entirely on amplitude? Is the loading employed sufficiently heavy to give any marked improvement in the phase relations? May we not find here a possible explanation of some of the discordant results obtained in the Paris experiments

Professor Howe.

of Breisig and Devaux-Charbonnel? I should like to ask the author for further information as to what constitutes drumminess. The references to it both in the paper and in the discussion have been very vague. Is the exact cause of the phenomenon fully understood? It appears probable that the best receiver on a short land line might not be the best on a loaded cable. It would be interesting to know whether tests have been made with receivers of different inductances, and if so, with what result.

Mr. Jacob.

Mr. F. Jacob (*communicated*): I would propose the term "spaced loadance" in contradistinction to "continuous loadance" to describe the addition of self-induction as obtained with coils and continuous iron-wire winding respectively. Leakance must be considered as a property of a dielectric which is not a function of its insulation resistance as measured after one or more minutes' electrification. The results of special measurements at Messrs. Siemens Brothers & Co.'s Works made on various dielectrics not only show, as those mentioned by Professor Breisig for viscous dielectrics, that $S/\omega K$ is a constant, the value of which is a function only of the material and independent of the capacity K, but that it is also independent of the temperature, at any rate between 0° and 25° C. The actual value of S/K for the core of this Channel cable given by direct measurement at 750 ∿ was 114.

The method proposed by Dr. Thompson of introducing inductance parallel with the dielectric displacement current was reintroduced by Professor Perry in his recent communication to the Physical Society as a "contrivance" to effect improvement in the telephonic transmission, but in the subsequent discussion was not favourably received by experts, for one reason that such "contrivance" was more adaptable for tuning to one particular frequency; but I would suggest that the most vital objection, in the case of a single-core cable, to such proposals is that a path is then afforded to the earth currents which would have free access to the conductor, while Professor Perry's proposal of the addition of a split condenser at each such inductance leak is hardly within the region of practical engineering in the present state of submarine cable manufacture. If Dr. Thompson would furnish a detailed specification of the actual electrical values of the "contrivance" he proposes for his five inductance leaks to be introduced in an Atlantic cable, it would be possible to determine from actual manufacturing data the dimensions and efficiency of such contrivance, as to which we are still in the dark.

Major O'Meara.

Major O'Meara (*in reply*): I wish first to thank those gentlemen who have called attention to various errors, typographical and otherwise, and I hope it will be found that the necessary corrections have been made in the paper as printed in the *Journal*. In the case of Appendix IX.A, some typographical and other errors had crept in, and these have made it advisable to reprint the table, which has been done. Various speakers have criticised the results of the speech tests made by Messrs. Cooper, Duddell, Judd and Kingsbury. Obviously such results could not be used as a reliable means of obtaining β, but they are of great interest as representing the opinion of the large body who will

Major O'Meara.

use the telephone in actual commercial service. Independent speech tests made by skilled members of the Post Office staff gave consistent results very near to those predicted for such tests before the cable was laid, and these are referred to on pages 324 and 356 of the paper. In commercial practice such tests are of great value, and in the hands of skilled men are capable of a considerable degree of accuracy. The statement that the new cable would permit communication as far as Astrakhan was merely illustrative, and was intended to show what length of unloaded line added to the new cable could be spoken over in the most perfect conditions of line and with latest types of apparatus; in the special conditions assumed, it is correct. Speech can be commercially conducted from call offices over a trunk line having a βl of 4·8. The Channel cable has a βl of only 0·332, thus leaving 4·468 for land line extensions, and it follows that an unloaded 800-lb. loop 1,990 miles long could be added to the cable (under perfect conditions). It will, moreover, be seen that this leaves a good working margin over the 1,700 miles mentioned. The figures on page 340 have given rise to some comment, and it should be explained that the electrical constants refer to single wire values. A footnote to that effect has been added. As explained on page 320, the table is from a foreign source, the only alteration made to it being to convert kilometres into knots.

Professor Fleming asked whether I think the dielectric current to which I alluded is a true conduction current. I think it is not, but rather a polarisation current. The Department's cables are tested with continuous current at 400 to 600 volts, and no indication of any leakage has been apparent in connection with such tests. Dr. Gustav Benischke* in an article discusses the losses in condensers subjected to alternating charges, and refers particularly to the losses of energy in the dielectric due to residual charges. I think the principal losses in the dielectric of a cable are of a similar nature. Such losses appear to vary as the square of the voltage. This seems to explain the observed fact that the dielectric losses in unloaded cables are less than in loaded cables of the same material. The average voltage in a loaded cable is maintained at a higher value than in an unloaded one. On account of such losses varying with the square of the voltage, care must be taken when making measurements with alternators to keep the impressed voltage down to the order of telephonic currents.

Mr. Dieselhorst says that some remarks I made at Paris leave the impression that difficulties are anticipated in repairing submarine loaded cables. I am afraid the remarks I made at Paris have been misunderstood. What I had in mind was that when an ordinary unloaded cable is repaired it does not matter what length is added when a fault is being removed, but in loaded cables difficulties might arise if repeated repairs were necessary near the same spot on account of variations in length interfering with the uniform distribution of the coils, but I did not and do not anticipate any serious loss of cable efficiency due to this course. It

* *Elektrotechnische Zeitschrift*, vol. 27, p. 693, 1906.

Major O'Meara.

must be remembered that in repairing our cables expedition is absolutely necessary, and cable ships have therefore to carry out repairs at times in spite of strong tides and winds. I agree with Mr. Kempe as to the satisfactory results of the insulation tests which have been made from time to time since the cable was laid, and I concur in his anticipation of a long life for the cable. In reply to Mr. Whalley, by the courtesy of Messrs. Siemens Bros., I am able to give the following explanation of the method of making the joints in the cable. "The difficulty is overcome by applying to the cable in the same closing machine, a second sheathing of wires over the first. The second sheathing may be laid on the cable only for a short distance on each side of the part of larger diameter, and the two sheathings will become only one over the last-named part, as the two sets of wires will now lie close together in a single layer, the length of lay being practically the same as that of the sheathing of the main part of the cable. Thus the tensile strength of the cable at the enlarged part will be greater than at other parts because of the greater number of sheathing wires, and without substantially affecting the pliability of the cable. When the first sheathing which has been applied in the usual manner approaches the part of the cable of increased diameter, the machine is stopped and the ends of the wires from the auxiliary bobbins are drawn through slotted lay plate and the die and laid over the first sheathing. Here they are secured by a wire lapping, and the machine being again started a second sheathing is thus applied over the first. When the coned end of the enlarged part arrives at the die, the latter is exchanged for one suited for the larger diameter, and as the wires are laid over the coned portion, they are gradually made to change from a double to a single sheath. The machine must be frequently stopped to change the die as the diameter increases. At the other end of the enlarged part of the cable, the operations just described are reversed, and when they have been finished the wires coming from the auxiliary bobbins are cut and wound up on the bobbins until the next enlarged part is drawing near to the machine."

In further reply to Mr. Whalley, I cannot say what type of cable the French Government proposes to lay, nor when it will be laid. The submarine cable is already specially protected at the cable ends, and no additional protection is thought to be necessary in England. As regards the variation of attenuation with frequency on unloaded cables, Mr. Hill's slide throws some light on the subject. The lengths in standard miles of each of the two cable circuits have been worked out and they agree. Mr. Whalley also asks if there is not an error in the horizontal line of Fig. 2, and whether it should not be either "β" alone or else "miles of equivalent standard cable." The description appears to be correct as it stands, *i.e.*, it is the βl deduced from observations on that type of cable known as "standard cable."

The terminal loss, with speaking apparatus close to the ends of the cable, is equivalent to 5 miles of standard cable, but the effect of the long length of land line at each end of the circuit is such that no loss

can be observed. Mr. Whalley also asked a number of questions as to the various tests. I have already referred to the speech tests, and I may add that the confusion which has arisen in the past owing to the use of different frequencies in calculation will probably not arise in future, as it was agreed at the recent Paris International Conference of Telegraph and Telephone Engineers to adopt 800 periods per second as representing the average frequency of the human voice. The tests made with the machines were very close, but they did not agree exactly, as the conditions under which they were made were not alike; for instance, the length in one test was 40 knots and in the other 41·704 knots; this appears to have been overlooked by some of the speakers. Major O'Meara.

Mr. Siemens has remarked that with regard to the diagram showing the repairs to the telephone cables across the Channel, the audience might think the repairs had been due to the bad manufacture of the cables, and he pointed out that fishermen's anchors were mainly responsible. I quite agree. I have had an analysis made of the repairs to the two telephone cables shown on the chart, and I find that the whole of the faults on the St. Margaret's to Sangatte cable were due to anchor breakages, and that of the faults on the Abbotscliff to Gris Nez cable the majority were due to anchor breakages, and one or two to the cable chafing on the rocks. Both cables were brass taped. I think this statement amply bears out Mr. Siemens' contention. In the case of the telegraph cable, which is not brass taped, faults have been traced to the *teredo navalis*.

In reply to Professor Thompson, I may say that we have made some experiments on leak loading, but have not obtained satisfactory results. If Professor Thompson will give some further information as to the amount of the inductance and the distances at which the coils should be inserted on a given subterranean cable, we should be happy to give the system a trial. There are, however, difficulties in the way of its application to submarine cables, as considerable trouble in localising faults on cables loaded with parallel inductances would be experienced, and we have to maintain cables in such a way that interruptions are of the shortest possible duration.

In reply to Mr. Gill, the cable referred to on the first line of Table A is the same as that mentioned in Appendix VII., cable E. The attenuation constant in Table A was calculated from the formula given in Appendix VIII., but that in Table VII. is given as it appears in the original foreign table from which it is quoted (see page 316 of the paper) and the formula used in connection with it cannot be stated. Mr. Gill anticipates that if the old Paris cable telephone circuits were superimposed an improvement of 10 miles of standard cable might be anticipated. Experiments on the Belgian cable, however, which is 55 miles in length and of exactly the same type as the old Paris cables, show that the superimposed or plus circuit is not quite so efficient as a direct unloaded pair in the same cable.

Mr. D. Sinclair anticipates difficulty with testing points on coil-

Major O'Meara.

loaded cables. Difficulties were experienced in the earlier stages, but these have now been largely overcome. If all the conductors in a cable were loaded, however, the test boxes would not be necessary, as the loading coils could be permanently jointed into the cable. Cable distribution heads are put in principally to give elasticity to the arrangements by enabling the number of loaded circuits in a cable to be increased from time to time in accordance with the requirements of the service. Such elasticity could not be obtained with continuously loaded cables.

In reply to Mr. Tremain, I may say that increased efficiency of long-distance telephone circuits, comprising a section of submarine cable, can generally be obtained more cheaply by increasing the weight of the land line conductors rather than those in the submarine section. A submarine line after loading is not so efficient as the same gauge of conductor unloaded in a land line. Of course, in cases where the utmost possible efficiency in cables is required the case is different, but in all cases inductance coils should be used as much as possible to give increased efficiency, and the gauge of wire be kept as small as practicable for a given "β."

In reply to Mr. Davis, it has been experimentally proved that the losses given on page 318 and stated to be due to eddy currents in continuously loaded cables are really due to that cause. The distortion observed in the Channel cable at a periodicity of 1,720 is what could be predicted from the known increase in effective resistance of the loading coils at that frequency.

Mr. Cook apparently assumes that a loaded 400-lb. circuit could be used as an equivalent for an 800-lb. unloaded aerial circuit, presumably because experience in America leads to that conclusion. After careful investigation, however, it is at least doubtful whether a type of loading sufficiently heavy to give that result could be maintained in our humid English atmosphere, particularly as the insulation of loaded heavy-gauge lines is known to be relatively low as compared with that of smaller gauge conductors. Possibly, however, a lighter type of loading not giving so marked an improvement might give satisfactory results. The matter is already under investigation, and this remark also applies to the subject of the improvement in communication with Ireland. It is a fact that the standard cable value of the two Irish cables in series is very high, but, as stated, it was just possible for experts to speak through them.

Mr. Campbell, as representing the National Physical Laboratory, is to be heartily thanked for the valuable information he has contributed, as are also Sir John Gavey and Mr. R. K. Gray for permitting the publication of such valuable matter. The magnetic material "stalloy," to which Mr. Mordey drew attention, has not been overlooked in its possible application to continuous loading. Experiments at the Post Office, however, have not yielded such high permeability under low forces as those shown on Mr. Mordey's curves. The permeability, for example, of the annealed material for $H = 0.01$ at 750 periods per

second seems to be 205 instead of 320. The figure 320 refers, it is true, to a ballistic test; but the permeability does not appear to vary very greatly between 0 and 750 periods per second. In the matter of hysteresis, too, our tests show that the loss, though small, is by no means negligible. A very valuable property of the material at these low inductions is its high specific resistance—some four or five times that of iron. **Major O'Meara.**

Mr. Mordey did not think that the effect of winding the stalloy on the conductor would much decrease its permeability, but that it might greatly increase the hysteresis. We have found, on the contrary, that the permeability may be almost halved, but that the hysteresis loss for a given induction is not much changed. The lowered permeability is the effect of permanent yield in the wire rather than of present stress.

Mr. Granville appears to think that for the same efficiency at the same price, an advantage would be gained if the gutta percha in the Channel cable were reduced, the copper increased, and then lightly loaded so as to obtain wider spacing of the coils; but if the gutta percha were reduced and the capacity consequently increased, it would be more economical to retain the present gauge of copper, as in that case the coils could be so spaced as to involve only a very small reduction in the "β" obtained in the present loaded Channel cable. There would be no insuperable electrical or mechanical difficulty in doing this. The superiority of lightly loaded heavy-gauge conductors over those of a less gauge more heavily loaded is not borne out by Post Office tests.

Mr. Cohen expressed the opinion that some 10 per cent. improvement would have been effected by placing the two loading coils, now situated half a knot from the ends, actually at the ends. Such a change would, of course, be detrimental to the efficiency of the cable considered by itself, so that the improvement contemplated must refer to transmission between inland stations. It is not clear, therefore, what is the quantity of which 10 per cent. is the suggested improvement. But even if this improvement is a reduction of 10 per cent. in the miles of standard cable equivalent to the submarine cable alone, it is not easy to see how so large an effect could be produced. A direct objection to the location of coils at the ends of the cable is that speech tests between the cable huts would then have been much less instructive; for the sending-end impedance of the cable when so arranged would be abnormally large, owing to the lumped inductance. The advantages to be derived by loading the land lines are fully recognised, but certain technical difficulties—chiefly climatic—have yet to be overcome before any practical success can be attained.

With regard to the use of a or β as a symbol for the attenuation-constant, the choice of β as a symbol is already so firmly fixed, in Germany, France, America, and generally in England, that the change would be ill-advised, even if it could be brought about; and there is really no advantage to be gained. Even if the complete propagation-constant is not "natural" when written $\gamma = \beta + j\,a$, why

Major O'Meara.

should it not be written $\gamma = j\alpha + \beta$; or, yet more alphabetically, $j\alpha + \beta = \gamma$? In Mr. Cohen's very interesting curves relating attention with frequency, he contrasts the horizontal line C, calculated by him for a loaded paper-core cable, with the inclined line D, reproduced from the last page of my paper, expressing measured values for the new Channel cable, and he asks what is wrong with the measurements. As shown on page 355 of the paper, there was no unloaded cable between the points at which currents were measured in these tests. It was precisely to avoid intermediate unloaded cable that the measurements were made at Dover instead of in London. There is, I think, no need to discredit the measurements on the score of the slope of the line. There are two effects of rise of frequency which we expect to declare themselves in an accompanying rise of attenuation; these are: (1) the increase of resistance of the loading coils, and (2) increase of leakance in the gutta percha. The core loss in the loading coils, as shown in Appendix IXA, is represented at 750 periods per second by a resistance of $(6 - 2{\cdot}25) = 3{\cdot}75$ ohms. If we take this loss as proportional to the square of the frequency, and if we take $\frac{S}{\omega K}$ as constant for change of frequency, S/K being 80 at $\omega = 2\pi \times 750$, then the values of the attenuation constant obtained by calculation are as follows:—

n.	β.	$\therefore \beta l$.
750	0·0170	0·68
1,000	0·0202	0·81
1,200	0·0231	0·92
1,500	0·0281	1·12
1,800	0·0338	1·36

These calculated values are plotted in Fig. M, the experimental curve being added for comparison. It is seen that the calculated curve slopes steeply, and is nowhere excessively divergent from the observed curve. In the calculation the capacity has been taken as constant and equal to the steady-charge value, whereas it is known that the high-frequency capacity is at all frequencies lower than the steady-charge value. This element of inaccuracy in the calculation may account for the non-coincidence of the two curves. The slope of the line D, therefore, in Mr. Cohen's diagram is only to be expected, and it is the horizontality of the line C which is surprising. One wonders whether there has been an omission to allow for the rise, with increase of frequency, in the resistance of the loading coils, and in the ratio S/K.

Mr. Rayner's experiments are very interesting, but I cannot give him the information for which he asks. The discussion has, however, brought out much valuable information on the subject of leakance. Major O'Meara.

In reply to Professor Howe's remarks respecting Mr. Kempe's formula $0{\cdot}01183\sqrt{KR}$; the difficulty is apparently one of definition. In any two sufficiently long loaded telephone circuits with similar characteristics we have equality of speech when $\beta l = \beta_1 l_1$, β and l being the attenuation constant and length of one circuit, and $\beta_1 l_1$ those of the other circuit; therefore $\frac{\beta_1}{\beta} = \frac{l}{l_1}$, that is, the lengths of circuit giving the same intensities of speech vary inversely as the β's, and

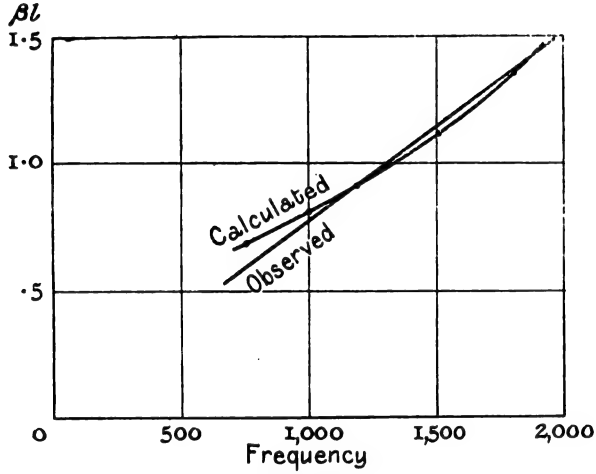


FIG. M.

as $\beta = 0{\cdot}01183\sqrt{KR}$ the efficiencies of the two circuits vary as their $\sqrt{KR}$. Incidentally the formula $\sqrt{\frac{1}{2}pKR}$ has only a very limited application for unloaded telephone circuits, that is, it may be used where the ratio of pl to R is small, but such is only the case with high-resistance cables. In telegraph circuits the frequency or speed, of course, varies as KR.

In telephony the amplitude is the principal factor determining the efficiency of speech, but in loaded cables clearness of articulation is obtained by placing the coils sufficiently near to each other. The frequency factor p does not appear in the attenuation formula used for loading, so that if it were not for the increase in the effective resistance of the coil, frequency would not affect the matter.

Drumminess is the name given to the characteristic "drummy" sound accompanying speech on cables having a K/R ratio of 0·003 or above (K being in microfarads and R in ohms). It is largely caused by the

Major O'Meara.

unequal attenuation of speech waves of different frequencies and the undue preponderance of some particular tone, coupled with the fact that the speech waves travel with different speeds according to their frequencies. Commercial receivers are not designed for use on one type of circuit alone but for general all-round use, as in telephony it is necessary to speak on all classes of circuit with the same apparatus. Tests have been made with different types, and those in use appear to be well designed for general purposes.

Referring to the alternator test of the cable described on page 323, Mr. Appleyard shows that the attenuation constant, as calculated by equating the observed current ratio to $\epsilon^{\beta l}$, is considerably lower than if the accurate expression is used, allowing for reflection effects. On the assumption that the values of the electrical constants used are absolutely correct, Mr. Appleyard is right, but it must be borne in mind that the values of the several factors employed in the shortened formula have not yet been precisely determined. What is definitely known at the present stage is that the formula—

$$\frac{R + R_1 + 80 L}{2} \sqrt{\frac{K}{L}}$$

can be used to forecast results as determined by speech tests when the steady current values of the electrical constants R, L, and K of the circuit and the effective resistance R_1 of the coil are allowed for. But in proceeding to deduce that the cable does not satisfy the specification, Mr. Appleyard gives an interpretation to the specification which is something of a strain to its spirit, if not to its letter. If a speech test is made by skilled observers on the loaded cable, sandwiched between some 10 miles of standard cable at each end, it is found that the speech transmission is somewhat better than when the loaded cable is replaced by one-seventh of its length of standard cable, as required by the specification. The insertion of the standard cable at each end decreases the attenuation due to the loaded cable in just such a practical manner as the air-lines may be expected to do; and it was the terminal loss thus removed which was contemplated in the phrase of the specification, "not including terminal losses."

In reply to Mr. Coote, I may say that the test in which 10 miles of standard cable was required as a terminal length to annul reflection losses was a speech test. In the case of the alternator test 20 miles of standard cable was found to be necessary. There was probably some difference of sensitiveness in the two cases. In the calculation of β, 80 has been used for the value S/K in the case of gutta percha wires, and the agreement obtained in practice is so close as to justify its use—at least until more extended experience permits of a more exact figure being arrived at. The direct-current value of the capacity was used, and this fact has now been made clear in the table. The Italy to Sicily cable referred to in slide shown on the screen at the Institution is that laid in 1905. 800 periods per second is mentioned in connection with

speech tests because the experimental value is mentioned in terms of miles of standard cable, and the corresponding β of the standard cable depends on the frequency assumed. Major O'Meara.

In reply to Mr. Shepherd, the formula given in Appendix X. (1) refers to single wires. In the Channel cable, owing to the long length of aerial line at each end, the terminal loss has small importance.

The CHAIRMAN: I am glad to see that the Institution is taking such great interest in these most interesting problems of telephony. The paper has dealt with many matters, but I do not propose to raise any questions to-night, except one point that Major O'Meara has mentioned in his reply, namely, the connection between the losses in the cable considered as a condenser and the factor that has been called leakance. These two are connected together, I believe, by a very simple formula, which will explain a great many of the discrepancies observed in the tests. You can take a short length of cable and measure its power factor, as we understand it as engineers, and by multiplying that power factor by the capacity per mile and by 2π times the frequency you will find a quantity which, added on to the true leakance of the cable, will give the correct attenuation constant which will agree with that measured on test. I will now ask you to accord a hearty vote of thanks to Major O'Meara for his most interesting paper. The Chairman.

The resolution of thanks was then put, and carried with acclamation.

Proceedings of the Five Hundred and Fourteenth Ordinary General Meeting of the Institution of Electrical Engineers, held in the Rooms of the Institution, Victoria Embankment, London, W.C., on Thursday, January 12, 1911—Mr. W. Duddell, F.R.S., Vice-President, in the chair.

The minutes of the Ordinary General Meeting, held on December 15, 1910, were taken as read, and confirmed.

The list of candidates for election into the Institution were taken as read, and it was ordered that it should be suspended in the Hall.

The following list of transfers was announced as having been approved by the Council :—

TRANSFERS.

From the class of Associate Members to that of Members—

James Anderson.
Edmund John Fox.
Hugh Fred. D. Jacob.
Archie Kelly.
Tom Percival Strickland.

From the class of Associates to that of Members—

Charles Borthwick Chartres.
George H. van Corbac.
Evan Parry.
Arthur Woolmore Wigram.

From the class of Students to that of Associate Members—

Joseph Walter Anson.
Alfred E. J. Hurst.
Edwyn Jervoise.
Chas. Richard Kemp.
Hasan C. A. Latif.
Middleton Leaviss Peel.
Sriram V. Setti.
Wm. Blair Smith.

From the class of Students to that of Associates—

John Horncastle Eddison.
Thos. Bertram James.

Messrs. H. Gurney Wood and F. J. Edmonds were appointed scrutineers of the ballot for the election of new members, and, at the end of the meeting, the following were declared to have been duly elected :—

ELECTIONS.

As Associate Members.

John Stevens Burgis.
John Edward Grant.
Thomas Hattersley Haigh.
Percy Gilbert Hay.
James Alfred Hunt.
Edwin Lack.
W. Forrest Marshall.
John Wallace Wyles.

As Students.

Thomas Harold Andrew.
Howard Henry Bagnall.
Edgar Alan Beavis.
Herbert Cecil Burrowes.
Frederick Carr.
P. Varada Chari.
Ernest John Chawner.
Shambu Nath Chopra.
Gowan Conningsby Clark.
William Edward Clark.
Lionel Ernest Cooke.
Herbert Sidney Craig.
Albert John Dannhorn.
Josiah Alfred Donald.
Edgar Thomas Driver.
Mehemmed Enver.
Augusto Fertado.
Henry James Gwyther.
Charles Levers Hall.
Leonard Ernest H. Harris.
Noel Francois S. Hecht.
George Henderson.
Cyril James Hews.
Philip Robert Hughes.
Harry Humphreys.
Eric Hutchison.
Harry Yule V. Jackson.
Samuel Colver Jarrett.
Bahadur Mirza Kazalbash.
Richard Lewis.
Arthur Lisle.
Gilbert Kelsey Loveday.
Leslie Alfred McDougald.
Ernest Goodeve Mabbs.
John Bernard Malpass.
Reginald Robert G. Mann.
Egerton Lloyd A. Mathias.
Albert Archibald Maytham.
Edward Raymond Mecredy.
Andrew Bell Mein.
Alfred Wellesley Miller.
Dennis Milner.
Martin James Mitchell.
Patrick J. Mitchell.
Ardeshir Kaikobad Modi.
Francis Lewis Otter.
Constantine G. Panayotopoulos.
Harold Edward Park.
Wilfred Arthur Perritt.
Harry Howard Phillips.
Arthur George Ramsey.
Arthur Rolfe.
Jessel Rosen.
Georg Friedrich R. Schmidt.
Arthur Mackenzie Searle.
August Sild.
Charles Percy Smith.
Sydney Horace Smith.
Victor Manuel Soffia.
Thomas Henry Solomon.
Henry Douglas Steers.
Herbert Alexander Stewart.
Tom Taylor.
Herbert Michael Theaker.
James Tudhope.
Henry Albert Underwood.
Percy Wardle.
Godfrey John Websdale.
James White.
Sydney Willis.
Thomas Golding Woolley.

The discussion on Major W. A. J. O'Meara's paper was concluded (see page 366), and the meeting adjourned at 10.5 p.m.

CONTROL OF ELECTRIC WINDING AND HOISTING ENGINES.

By Dr. E. ROSENBERG, Member.

(*Paper received November* 11, 1910, *read before the* MANCHESTER LOCAL SECTION *on December* 6, 1910.)

SUMMARY.

The paper first discusses in brief the general features of the different systems of winding engines, viz., direct-current winding motors with controlling generator (Ward-Leonard, Ilgner), direct-current winding motors with rheostatic control, and alternating-current winding motors with rheostatic control. The control apparatus is then described and illustrated.

The dependence of the motor speed in each of the systems on the load and on the controller resistance is discussed.

A considerable part of the paper is devoted to investigations on the use of the motors as electrical brakes, and the conditions of regenerative control, braking with counter-current, and braking by supplying current to independent resistance are considered. The effect of speed variation and excitation upon the torque is investigated with direct-current motors, and with alternating-current motors excited by direct current, and test results are given.

Lastly, the application of the eddy-current brake is mentioned, test results of different sizes of eddy-current brake are analysed, and the difference between such apparatus with copper and iron armatures is explained.

Four years ago, in this Institution, three most interesting papers by C. B. Sparks,* W. C. Mountain,† and G. Hooghwinkel‡ were read, dealing with electricity in mines in general, and with the question of electric winding engines in particular, and these papers, as well as the heated discussion following them, brought out all the arguments in favour of and against electric main winding engines. By all parties it was agreed that hoisting engines may with advantage be driven by electricity, but in respect to main winding engines the views as to the economic possibility of an electric drive were seriously divided.

Times have passed, and electric winding has developed at home and abroad, and at present there are in Great Britain and the British Colonies

* *Journal of the Institution of Electrical Engineers*, vol. 36, p. 477, 1906.

† Ibid., p. 499.

‡ Ibid., p. 506.

alone such a great number of winding engines in actual service, or in process of erection, that one can safely say that for certain conditions, at any rate, electric winding has not only proved economically possible, but a distinct economic success. Especially in cases where power can be bought cheaply from a public power station, or where the private power station can be used to supply either several winding engines, or at the same time a great variety of motors with fairly good load factor, the advantages of cheap power production by the adoption of large and economical working units has more than balanced the necessity of

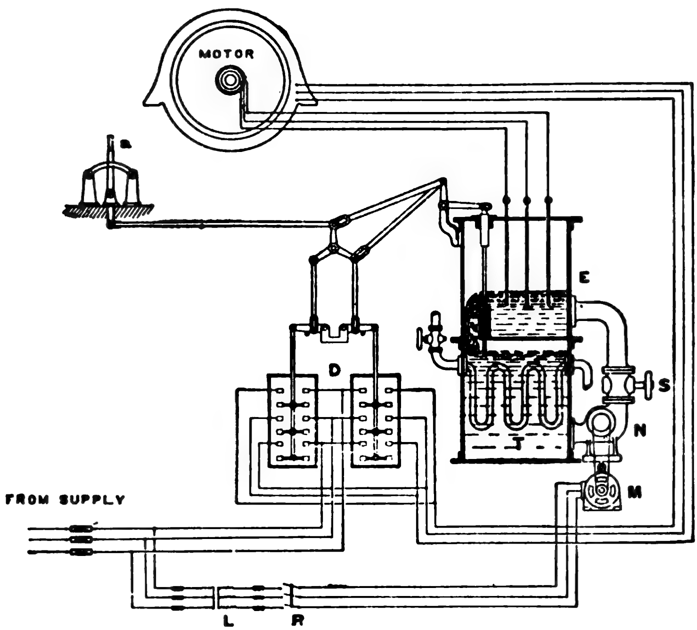


FIG. I.

double conversion of energy. In many cases the electric winder is not only the cheapest in working, but also the cheapest in first cost, and when this most important foundation of economic advantage is established, the user also appreciates the additional amenities provided by the excellent technical features of electrical drive, namely, the ease and safety of control, the entire absence of jerks, and the perfect regularity of drive from full to creeping speed.

So far, the direct-current motor and the polyphase induction motor have generally been used for electric winding engines of large capacity, and only these will be considered in the present paper. Single-phase commutator motors could be used, but are expensive, and not so efficient

as the other motors. Single-phase induction motors present difficulties of control, and, therefore, will rarely be used for direct driving of large winding engines.

As far as the control of direct-current and polyphase induction motors is concerned, we have mainly to distinguish between rheostatic control used for either type of motor, and Ward-Leonard control used only for direct-current motors, for which a special controlling generator is employed. The rheostatic control, that is, the starting from a substantially constant busbar voltage by the insertion of a gradually decreasing resistance, inserted either in the armature circuit of a direct-current motor, or in the rotor circuit of an induction motor, can be done either with metallic or liquid resistances. For large motors, and nearly always for induction motors, liquid controllers are employed. Fig. 1 shows the general principle of an induction motor controller for large output. *a* is the controlling lever used by the driver, acting at the same time on the reversing switch D for the stator, and on a sluice-gate P limiting the height of the liquid in a tank E, which is fitted with three stationary electrodes connected to the rotor slip-rings. The liquid is kept in constant circulation by means of a motor-driven circulating pump N, and is cooled in the lower part of the tank by means of cooling coils T. The circulating speed of the liquid can be regulated by means of the valve S. The main motor is, as a rule, wound for high voltage; there is a step-down transformer L inserted for the pump motor M.

With such an arrangement the driver is not able to cut out the rotor resistances too fast. He can fix the position of the sluice-gate when starting, but the water-level is only gradually raised to this position, according to the pump speed and the opening of the regulating valve. The solution is used over and over again, and only requires occasional replacing of the evaporated water. The cooling water (just as in a surface condenser) is not allowed to mix with the solution. A photograph of a liquid controller for a 1,400-H.P. 3-phase motor is given in Fig. 2. Fig. 3 shows the induction motor controlled by this apparatus coupled to a winding drum.

Although the slow-speed motor thus required is more expensive than a high-speed motor, and also has a lower power factor, the direct coupling is, for large outputs, very often adopted, as these disadvantages count for little compared with the advantage of increased efficiency and elimination of the mechanical transmission gear, provided the drum speed is not too low to permit of a reasonable motor design.

Ward-Leonard Control requires a special direct-current generator either engine driven or, more often, driven by an electric motor supplied with current of constant voltage (either alternate current or direct current) from general busbars (Fig 3A). The generator part is a direct-current generator with separate excitation, which can be changed between the limits of zero and a positive and negative maximum. The winding motor (Fig. 3B) is externally constant excited, and its armature connected to the generator armature without any switches or controller. The speed of the winding motor is, therefore, in approximate propor-

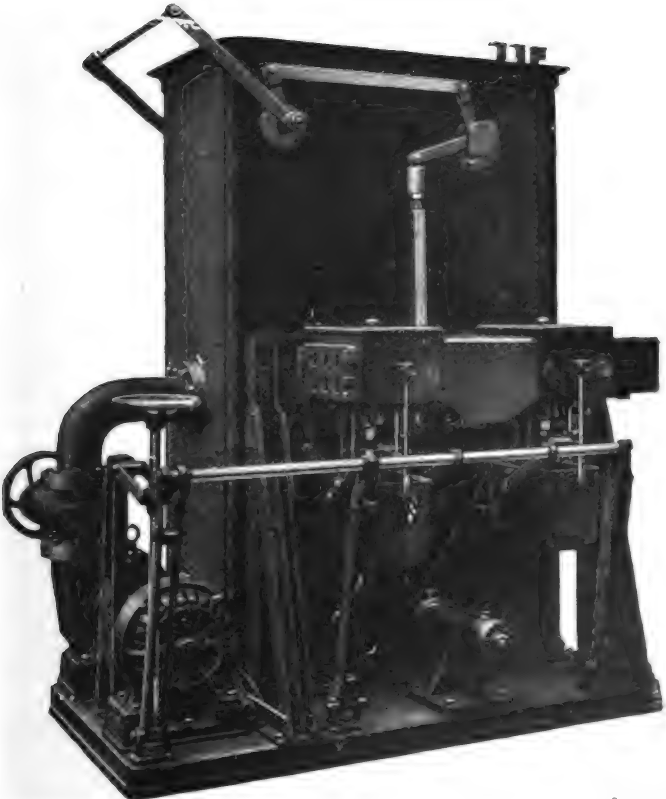


Fig. 2.

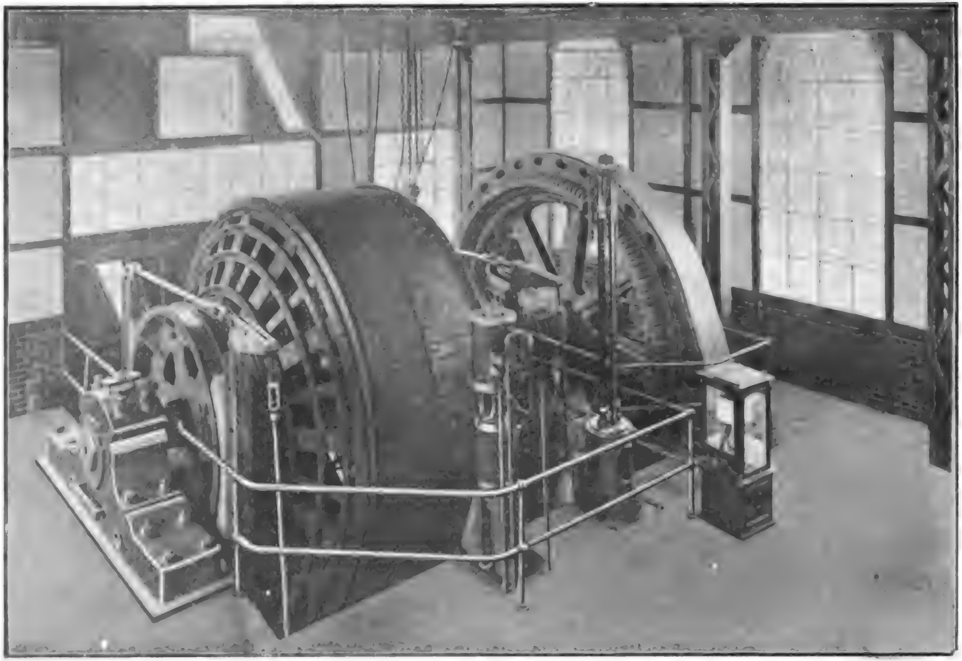


FIG. 3.—Direct Coupled Slow-Speed Three-phase Westinghouse Motor.

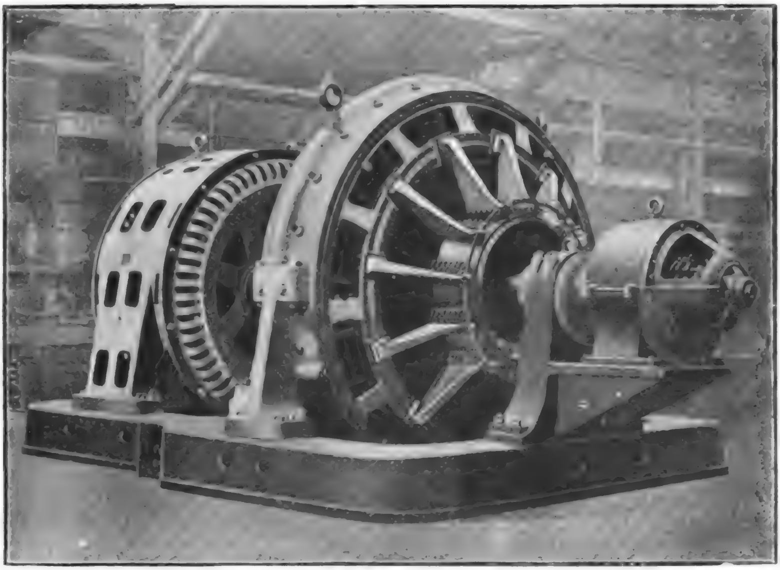


FIG. 3A.—1,200 k.w. Motor generator with Exciter, 420 revs. per minute (Peak Load 2,400 k.w.).

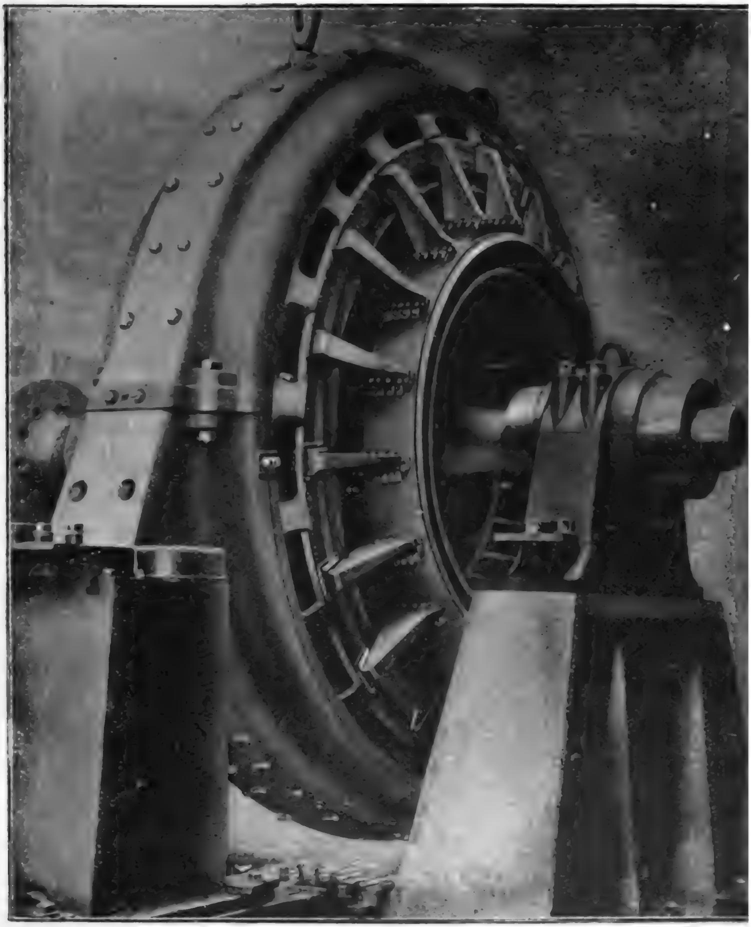


FIG. 3B.—1,500 Direct-current Winding Motor, 98 revs. per Minute (Peak Load 3,000 H.P.).

FIG. 4.

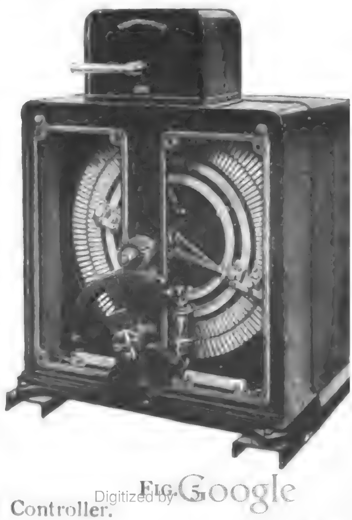


FIG. 5.

Ward-Leonard Controller.

tion to the voltage of the controlling generator, and the direction of rotation is directly dependent upon the direction of the exciting current of the generator. A small shunt controller gives perfect control over the whole machine.

Figs. 4 and 5 show this controller drawn to approximately the same scale as Fig. 2. If the arm with the contact brushes visible in Fig. 5 is in the vertical position (corresponding to the "off" position of the driver's lever, see Fig. 4), then the generator is not excited, and a connection is made in the generator windings which counteracts the residual magnetism. By a gradual movement of the contact arm in clockwise direction, the generator will be excited, and the generated voltage will produce a certain direction of rotation of the winding motor. For a movement of the contact lever in counterclockwise direction from its neutral position, the generator voltage, and with it the rotation of the winding motor will be reversed. The photographs show at the top of the shunt-regulator another small controller with a handle which is mechanically interlocked with the main lever. This small controller represents merely a switch used in case of winding intervals of long duration for switching off the excitation of the winding motor ; a discharge resistance is fitted to this switch.

The Ward-Leonard system gives wonderful ease of control, and very light and simple controlling apparatus ; the amount of machinery, however, is increased, as are the initial costs, and the great advantage of practically negligible starting losses is partly counterbalanced by the loss of efficiency in the motor-generator. As far as current consumption is concerned, the Ward-Leonard system will show to great advantage if starting and braking periods are of comparatively long duration, and winding intervals short, also if trips with reduced speed (for instance, for men winding), are of frequent occurrence ; whereas the straight rheostatic control will show up best if full-speed runs and winding intervals represent a very great portion of the whole working time.

Very often it is considered essential to guard against interruptions of the supply, and to provide means which would enable the continuation of at least one trip. The Ward-Leonard system lends itself very nicely to a storage of energy by coupling with the motor-generator a flywheel (Ilgner system). This also allows of equalising the demand on the power station by providing the motor of the Ilgner set with a considerable drop in speed between no load and overload, and thus giving the flywheel an opportunity to discharge a part of the stored energy when the load grows, and to store energy between the periods of work. Instead of the flywheel, a third machine, viz., a direct-current generator, can be used, which works in parallel with a storage battery.

In case of direct-current winding motors working direct from the busbars, it is possible to use for such purposes a direct-current motor coupled to a flywheel, and fitted either with special field windings, or with an automatic shunt rheostat, which, according to the momentary requirements, will cause this machine to work either as a motor or as a

generator, and so either to store energy in the flywheel or to convert the stored energy into electrical energy. An accumulator battery, either with or without automatic booster, will serve the same purpose.

In case of alternating-current winding motors similar ends have been achieved by running from the mains a synchronous motor coupled to a flywheel, which motor, in case of failure of the line current, will act as a generator and feed the winding motor; or by running a rotary converter the direct-current part of which is connected to a direct-current flywheel motor. In this latter case the equalising action of the flywheel during the ordinary service is also made use of (Westinghouse Equaliser System).

The aim of the present paper is mainly to study the electrical conditions of control, and more particularly the conditions for braking in the different systems. We have always to reduce the speed at the end of a trip and to bring the winding engine to a standstill, but very often we have also to lower unbalanced loads instead of lifting them, and in this case the winding motor, if it is to be used at all, has to work as a generator converting mechanical energy into electrical. In many cases the change from positive to negative motor torque will occur during each trip.

If no tail rope is used, and the load on the up-going cage is just balanced by the load on the down-going cage, then the rope weight will, in the first half-trip, exercise a positive, and in the second half a negative torque, and the winding machine has at first to act as a motor and then as a brake.

Ward-Leonard System.—As long as the speed of the Ward-Leonard motor-generator is kept constant, the shunt regulator of the controlling direct-current generator determines fully the E.M.F. of the controlling machine, and if the winding motor is mechanically driven from outside, the speed of the constantly excited winding motor will attain a value which gives an E.M.F. in the winding motor only slightly higher than that of the controlling machine, because already a slight difference will give rise to a circulating current of sufficient magnitude to balance the torque impressed from outside.

We have to make certain assumptions to determine how much the speed of the winding engine will differ for a given position of the controlling lever, whether the machine is working as a motor lifting a certain load or as a generator driven by the lowered load.

We shall assume at first that the exciting voltage is kept constant, and that there is no flywheel and no artificial slip in the motor-generator, also that the primary frequency and voltage remain constant. The slip of the induction motor driving the controlling dynamo will be proportional to the load, and at full load will be at least 2 per cent. The controlling machine, which as a rule is fitted with commutating poles, might for constant speed have a drop in voltage from no load to full load of 5 per cent. of the maximum voltage, and the winding motor will have a similar drop in speed, say again 5 per cent., for constant voltage on the terminals from no load to full load. That would mean

that the difference of the motor speed between no-load torque and full-load torque due to all causes combined will be approximately 12 per cent. if the induction motor has only 2 per cent. slip. If the winding motor has to exercise a negative torque of half the value of the normal working torque, the difference in speed will grow to 18 per cent.

This difference of 18 per cent. of the full speed, however, remains nearly constant in its absolute value, and therefore grows in proportion if the controller lever is put into a position for a low speed. For half excitation the lifting speed for normal load will be about 39 per cent. of the full (no-load) speed and the lowering speed for a load which would require half braking torque will be about 56 per cent. of the full speed.

If an Ilgner set with increased slip is used, or if the exciter is coupled to the shaft of the motor-generator and its voltage is not automatically kept constant, the differences will be even greater. It is therefore necessary also in case of Ward-Leonard control to use a speed indicator, and not to depend upon a positive relation between the position of the control lever and the speed of the winding engine. In general, it can be said that the method of braking with the Ward-Leonard arrangement is nearly perfect in so far as the movements of the controller lever in order to come to rest are pretty nearly the same whether the motor is driving or driven, and that a very great braking torque can be obtained from the motor. Normal current in the motor armature when used as a brake represents more than normal torque on the winding drum. If the controller is not too quickly handled, there will be no unusual stresses either in the electrical or in the mechanical parts, which, of course, in any case have to be built to cope with the always occurring reversal of power.

The calculation of the speed variations possible for certain positions of the controller were made under the assumption that current can be returned to the line. If, however, the line voltage fails, be it that a circuit breaker comes out or by a similar occurrence, then the state of affairs alters considerably. If a flywheel of sufficient capacity is connected to the motor-generator, the energy supplied by the lowering load will speed up the flywheel to a permissible value. If, however, no flywheel is applied, then the motor-generator would soon speed up to a dangerous limit, and therefore it would be necessary in such a case to apply the mechanical brakes practically at the instant that the circuit breaker comes out.

In a system which instead of the flywheel uses a third electric machine connected to an accumulator battery, the storage of energy could, of course, go on, as a battery even if fully charged is always capable of receiving energy by being overcharged.

Rheostatic Control of Direct-current Motors.—We will now investigate the case of using the motor as a brake if rheostatic control is employed, the motor being supplied with current from general busbars. The first case would be that of a direct-current shunt motor fed from

direct-current busbars. This case mainly applies to comparatively small motors, up to a few hundred horse-powers. The direct-current motor can be built for combined series and shunt regulations, viz., variable resistances inserted in the armature circuit and a shunt regulator in the exciting circuit. This reduces the rheostatic losses in starting as the speed regulation effected by the shunt regulator is done without loss. For all speeds within the range of shunt regulation braking is done most effectively without any additional apparatus, because the motor, if its armature is connected to the busbars without intermediate resistances, will work as a generator if driven from outside and return power to the line.

For a given position of the shunt regulator (with the series resistances cut out) the motor when working as a generator and exercising half full-load brake torque will develop (under above assumptions) a speed approximately 7 per cent. higher than the speed which it would develop for the same controller position if it was exercising full torque as a motor. It is assumed that the busbar voltage remains constant.

For other positions of the controller, when resistance is inserted in the armature circuit, the conditions are entirely different. First of all, the speed of the motor, even when working as a motor, will greatly vary according to the load, and a certain controller resistance which for full load reduces the motor speed by 20 per cent., will for 100 per cent. overload produce approximately 40 per cent. drop, and for no-load no appreciable drop. In other words, with resistance inserted in the armature circuit, the E.M.F. impressed upon the motor armature is no longer approximately constant but will vary with the load. Working as a motor, the E.M.F. of the machine will be considerably smaller than the busbar voltage, and working as a generator the machine will have to develop considerably greater E.M.F. in order to return power through the resistance to the line. Using again our example of 100 per cent. motor torque and 50 per cent. brake torque, a value of the series resistance which gives a full-load motor speed of 90 per cent. of the no-load speed would allow approximately 105 per cent. generator speed; 80 per cent. motor speed would correspond to 110 per cent. generator speed; 50 per cent. motor speed to 125 per cent. generator speed; and a position for creeping speed of the motor, say 5 per cent., would allow a generator speed of approximately 148 per cent. A position of the controller which allows for the motor before starting, less than normal current, would allow a very dangerous speed for the same machine when generating. The above figures represent steady values, assuming that (as in deep shafts) the controller position can be maintained long enough to obtain these values.

These figures make it clear that such controller positions are in general not suitable for lowering loads, and that this regenerative control will mainly be used with the controller in "full-on" position. It will often be the case that to start the lowering trip motoring current has to be sent at first into the motor. But it is

essential that the controller lever should soon be pushed to the "full-on" position, and kept there in order that the speed may not grow beyond control.

The regenerative control cannot be used to slow down the motor at the end of the trip. For this, either the controller has to be moved quickly into the "off" position and the mechanical brake applied, or the controller may be quickly moved beyond the "off" position and the first steps for the reversed movement used, which allow outside current to enter into the motor in such a direction as would be needed for lifting the load which is being lowered.

In the case of regenerative control the winding machine has to generate an E.M.F. in excess of the busbar voltage, and the braking current is defined as the difference of generated E.M.F. and busbar voltage divided by the controller resistance (including armature resistance). For reversed controller position (braking with counter-current) the E.M.F. of the winding machine acts in the same direction as the busbar voltage and the braking current is defined as the sum of both voltages divided by the controller resistance.

Let E be the busbar voltage, and n the no-load speed of the motor, and let I_1 be full-load motor current, and R the resistance of the controller (including also the resistance of the armature circuit), and let E be the E.M.F. of the motor corresponding to this resistance R when the motor is exercising full-load torque, and developing a speed n_1. Also let E_2 be the E.M.F. of the winding machine acting as a generator for the same resistance R and producing a braking current I_2 at a speed n_2, then we have the following formulæ:—

The braking current—

$$I_2 = \frac{E + E_2}{R}$$

$$E_2 = I_2 R - E.$$

$$n_1 = \frac{E_1}{E} n = \frac{E - I_1 R}{E} n.$$

$$n_2 = \frac{E_2}{E} n = \frac{I_2 . R - E}{E} n.$$

During the moment of slowing down the value of the braking current I_2 is not self-defined; it is clear that according to the time we allow for slowing down, the momentary value of the braking current will be higher or lower, and that, generally speaking, any value of the resistance R (below a certain limit) can be used for stopping, and that the stopping period will be the shorter the smaller the applied resistance R is.

It will also be seen that the limiting value (R critical) of the resistance for slowing down is defined by—

$$R_{crit.} = \frac{E}{I_{stat.}},$$

if $I_{stat.}$ represents the current in the motor armature which would keep static equilibrium to the load torque (including friction).

Higher values of the resistance give acceleration, lower values retardation. If the load is brought to rest by first applying a smaller resistance, then the critical resistance position can be used to keep the load floating.

In case the speed throughout the whole lowering trip has to be kept lower than the speed which the motor develops with all the armature resistance cut out, for instance, for lowering of men, counter-current must be used during the whole trip.

In general, we want for braking purposes a current which is lower than the normal motor current for lifting, for the efficiency of the mechanical gear will, of course, necessitate an increase of the motor torque above the load torque, and reduce the generator torque under the load torque; whereas, therefore, for lifting the resistance will have to be smaller than $\frac{E}{I_{stat.}}$, it will be necessary for continuous braking with counter-current to have a resistance larger than $\frac{E}{I_{stat.}}$, and for $I_2 = \frac{I_1}{2}$ the resistance will have to be bigger than $\frac{2\,E}{I_1}$. Therefore, a metallic controller which is to be used for braking with counter-current will have to be made of more than double the resistance of an ordinary controller, and a separate portion of the controller must be used for braking.

Regular braking with counter-current is a very safe, but naturally wasteful method, as not only is no energy returned to the line, but a current from the line is consumed equal to the brake current. The energy wasted in the controller represents the sum of the energies drawn from the line and generated by the load. Whether this waste of energy is objectionable or not depends upon the frequency and duration of down trips with unbalanced load. If such trips, for instance, occur regularly only once a week for an hour or two, then the waste of current during 1 or 2 per cent. of the whole working time will not be of much consequence as regards the total working cost of the whole apparatus. In other cases with frequent unbalanced down trips the waste of current might represent a serious item.

Rheostatic Control of Induction Motors.—With a polyphase induction motor used as a winding motor, the conditions are exactly analogous to those of a direct-current shunt motor (without shunt regulator) fed from busbars. If the rotor is short-circuited, the machine will, for a slight increase in speed, act as an induction generator and return power to the line. With the slip-rings directly short-circuited, the difference between no-load and full-load speed of the motor would be approximately 2 per cent., and the speed of the motor working as a generator on half-load would be only approximately 3 per cent. above the full-load motor speed. Liquid controllers, however, are seldom completely short-circuited, and, therefore, the speed difference might

be nearer to 6 or 8 per cent.—just about the same as previously mentioned for shunt motors.

In order to brake the motor down to lower speeds, counter-current is required, and exactly the same relation for the controller resistance holds good as that already developed for the shunt motor. Driving the motor at over-synchronous speeds with resistance inserted (controller in lowering position) would here also cause too high a speed to be reached.

So far, we have considered braking methods which do not require any additional apparatus, or any connections different from those which are made in the normal process of controlling the motors as motors. We shall now consider the possibility of braking methods with different connections, and also with additional apparatus.

Direct-current Motor as Dynamic Brake.—We can disconnect the armature of a direct-current motor from the line, and connect it either to a part of the resistance of the starting controller, or to another resistance. If the machine is constantly excited from the busbars, the braking torque or braking current will be in direct proportion to the speed of the motor, and in inverse proportion to the controller resistance; therefore, in order to keep perfect electrical control of a constant lowering load from the start up to the very end of the trip, it would be necessary at first to increase, then to reduce the outside resistance gradually in proportion to the desired momentary speed. Of course, a constant resistance could be used which would only limit the steady speed of the lowering load, and some other means could be used to bring the load to rest at the end of the trip. For instance, a resistance which in series with the armature would allow full-load starting current to be taken from the line, will, when connected across the armature, allow a braking current equal to half full-load current for approximately half-speed of the machine driven by the load. To allow full lowering speed for a brake torque equal to half full-load torque, a controller resistance of the double value would be required, provided that no regulation in the shunt field of the motor is intended.

Here we have the same peculiarity as with all other braking methods where a resistance in the armature is applied, that an increase of this resistance increases the speed of lowering, whereas, for the motor working as a motor, an increase of resistance reduces the speed. An important fact in connection with this braking method is that for a given speed the braking torque is nearly in inverse proportion to the controller resistance. For zero resistance the braking torque would be enormous for every appreciable speed, and the machine will, therefore, soon come to rest, or only develop a creeping speed.

*Induction Motors with Direct-current Excitation as Dynamic Brakes.**—This is entirely different in an induction motor, a part of which is

* Mr. R. E. Hellmund, Pittsburg, has recently published an interesting article on this subject in *Elektrotechnik und Maschinenbau*, vol. 28, p. 837, 1910, which is partly followed and partly enlarged in the following investigations. The latter ones, for the greater part, had been finished before perusal of Mr. Hellmund's article.

excited by direct current (either the rotor or stator) and the other part connected to a resistance. As a rule, the stator which is normally wound for high-voltage alternating current will be connected to a low-voltage direct-current supply and the three slip-rings of the rotor connected to a resistance of the corresponding number of phases. Such a machine represents an alternating-current generator with stationary field, the exciting winding of which is distributed in the slots, and with a rotating polyphase armature connected to ohmic resistances. The frequency of the generator will, of course, vary according to the speed, and would be equal to the supply frequency if the rotor were rotating at full motor speed. The machine is distinguished from ordinary alternating-current generators mainly by the fact that the air-gap is exceedingly small, and that, therefore, the armature reaction is exceedingly high. If the stator is excited with the equivalent value of the full-load stator current and the rotor rotating at normal speed and giving a voltage equal to the open circuit rotor voltage and a current equal to full-load rotor current, then it will be found that the ampere-turns on the stator are only a few per cent. in excess of the rotor ampere-turns, whereas, in an ordinary alternating-current generator the field ampere-turns are generally twice as much as the full-load armature ampere-turns.

This big armature reaction has a very important bearing on the behaviour of the machine, because it is only for comparatively small armature reaction that it can be said that at constant speed the torque will be in nearly inverse proportion to the outside resistance. As soon as the armature current exceeds a certain limit a reduction of the outside resistance will not only not increase, but even reduce the braking torque, because a slight increase in armature current is accompanied by a more than proportionate reduction in field strength. With short-circuited slip-rings the torque obtainable at higher speeds is very small.

If direct current is applied to produce a magnetising effect in a 3-phase winding there are two arrangements which can be used without disarranging the windings :—

1. To connect one terminal to the negative supply, and the remaining two terminals in parallel to the positive supply.
2. To connect one terminal to the negative supply, the second to the positive supply, and leave the third terminal free.

A different direct-current voltage and current is required in cases 1 and 2, in order to produce the same effect that a certain 3-phase current would produce.

We know that the rotating field in a 3-phase motor can be considered to be of constant value at every moment. If we, therefore, preserve the instantaneous distribution of the current in the three phases by replacing the instantaneous value of the alternating current

in every phase, by direct current of the same value, we shall have a stationary field of the same value as the previous rotating field.

In a star-wound machine, with terminal No. 1 connected to the negative direct-current supply, terminals Nos. 2 and 3 in parallel connected to the positive supply, the current in phase 1 will have the double value and opposite direction of the current in phases 2 and 3. Whereas, the current in phases 2 and 3 flows from the terminals to the star-point (negative direction) it will flow in phase 1 from the star-point to the terminals (positive direction).

This is a picture of just what happens when, in a 3-phase system, the current in phase 1 is at the crest of the wave. Let us call the measured (root mean square) value of the alternating current in each phase C, then the momentary value of the current in phase 1 is 1·414 C, and of the current in phases 2 and 3, 0·707 C. It is, therefore, quite clear that in this connection the direct current replacing the 3-phase excitation will have to be of the value 1·414 C.

Let us assume a star-wound machine, and connect only two of the terminals to the direct-current supply. Then the current in the third phase is zero, the current in phases 1 and 2 of the same value but opposite direction. This corresponds to the moment in which, in the 3-phase machine, the current in phase No. 3 goes through zero, whereas the current in the two other phases has the values of $+\sqrt{\cdot\frac{3}{2}}\,C$ and $-\sqrt{\cdot\frac{3}{2}}\,C = +1{\cdot}23\,C$ and $-1{\cdot}23\,C$. In this connection, therefore, the equivalent direct current will be 23 per cent. higher than the measured value of the alternating current.

The watt losses in the first case are, if R represents the resistance of one phase :—

$$(1{\cdot}414\,C)^2\,R + 2\,.\,(0{\cdot}707\,C)^2\,R = 3\,C^2R,$$

and the same in the second case, viz.:—

$$2\,(1{\cdot}23\,C)^2\,R = 3\,C^2R.$$

Therefore, the direct-current voltage in cases 1 and 2 applied is in inverse proportion to the current.

Exactly the same holds good for delta connection. There also the direct current, if connected only to two terminals, has to be 23 per cent. in excess of the measured alternating-current value, whereas, if one terminal is connected to the positive, and the two others to the negative supply, the value of the current is 1·414 C.

We could excite the stator with a current as above, corresponding to the full-load stator current, and could insert in the rotor a resistance which would just allow normal rotor current to flow. In this case the magnetic conditions would be exactly the same as in an induction motor working with full-load current at any moment of the starting

period, and it is therefore clear that we should have normal torque at the circumference of the rotor. There is only the slight difference

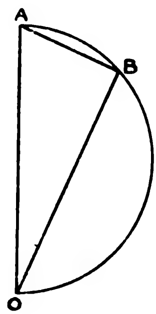


FIG. 6.

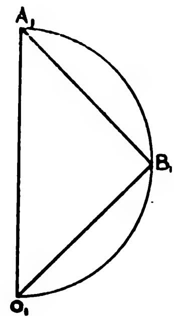


FIG. 7.

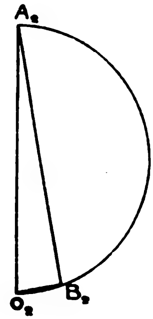


FIG. 8.

as to the torque on the rotor shaft, that for the motor we have to deduct the losses, whereas in the generator we have to add them.

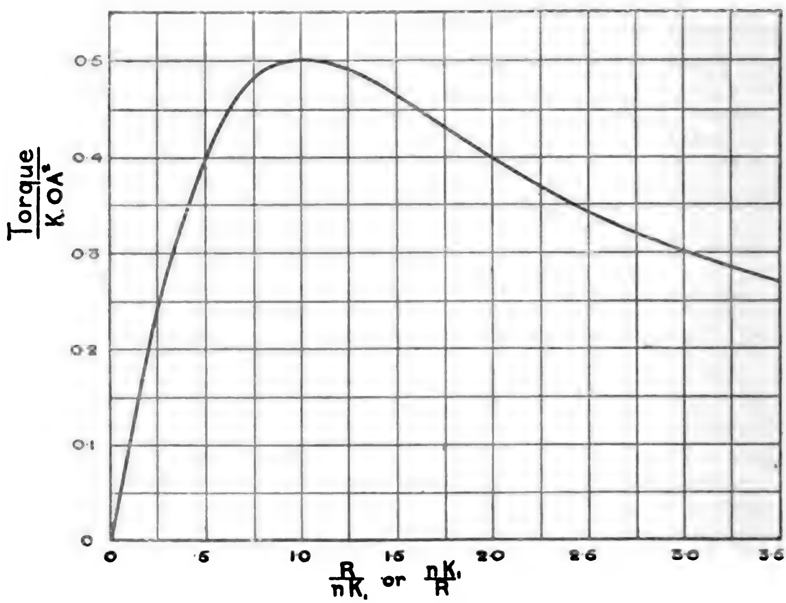


FIG. 9.

The normal full-load brake torque on the shaft can therefore be obtained under these conditions with a current which is a few

per cent. lower than the above-named value of 1·41 C and 1·23 C respectively.

This is not necessarily the greatest torque we can obtain for this excitation, as a very simple investigation will show us, based on the well-known Rothert diagram for alternators. Assuming the resistance to be free from self-induction, we may apply the simple diagram of Fig. 6, in which O A represents the total ampere-turns of the stator, A B the demagnetising ampere-turns of the rotor, and O B the resultant ampere-turns which are responsible for producing the real field (effective field + ineffective leakage field). In Fig. 6 it is assumed that the resistance inserted in the rotor is comparatively large, and therefore A B comparatively small, and O B great. In Figs. 7 and 8 the outside resistance is gradually decreased, and therefore also the resultant field $O_1 B_1$ and $O_2 B_2$. The points B as *points* of a right-angled triangle are all to be found in circles over O A as diameter.

If the saturation is low, we can say that the resultant field will be in proportion to the resultant ampere-turns O B. And as the torque is proportional both to armature current A B and resultant field O B, it can be represented by the area of the right-angled triangle O A B. Therefore, clearly, the maximum torque would be obtained for a value $A_1 B_1 = O_1 B_1 = 0{\cdot}707\ O_1 A_1$ (see Fig. 7).

Suppose we had a motor which, normally at full load is working at a power factor 0·8, *i.e.*, with approximately 80 per cent. current in the rotor, and 60 per cent. wattless current (no-load magnetising current and additional magnetising current for leakage). If we imitate these conditions in the motor used as brake, the torque will not be as high as if we reduce the rotor current from 80 per cent. to approximately 71 per cent. These latter conditions will give a torque about 4 per cent. higher than in the first case.

For a motor with 0·9 power factor, the maximum obtainable torque as a brake could be increased by nearly 25 per cent. if the field had such a low saturation that it was capable of 60 per cent. increase in value with corresponding increase in field ampere-turns.

In weakly saturated machines the E.M.F. in the armature will be proportional to O B and proportional to the speed of the armature—or, in other words, to the frequency of the rotor current. As the total resistance of the armature current (outside resistance plus internal resistance of armature and contact resistance of slip-rings) is represented by the quotient of voltage and current, we find that the tangent of the angle O A B, multiplied by the speed, represents the resistance.

Our diagram is correct for all frequencies, as a given value of the stator and rotor current determine the resultant ampere-turns, and therefore the resultant field. We can, therefore, get the same maximum torque at any speed so long as we change the resistance in the rotor circuit in strict proportion to the speed.

The general character of the speed-torque-curve or of the resistance-

torque-curve for a given excitation is easily determined. Assuming a weakly saturated machine we have, with reference to Fig. 6—

$$\text{Torque} \ldots T = K.OB.AB = K.OA^2 \sin A \cos A,$$

K being a constant.

$$\text{Resistance } R = K_1 . n . \frac{OB}{AB} = K_1 n . tg . A,$$

K_1 being another constant, and n representing revolutions per minute.

$$\sin A = \frac{R}{\sqrt{R^2 + n^2 . K_1^2}}$$

$$\cos . A = \frac{n K_1}{\sqrt{R^2 + n^2 K_1^2}}$$

$$T = K.OA^2 . \frac{R n K_1}{R^2 + n^2 . K_1^2}.$$

This again can be represented either as—

$$T = K.OA^2 . \frac{\frac{R}{n K_1}}{\left(\frac{R}{n K_1}\right)^2 + 1}$$

or—

$$T = K.OA^2 . \frac{\frac{n K_1}{R}}{1 + \left(\frac{n K_1}{R}\right)^2}.$$

Fig. 9 shows, therefore, at the same time how the torque varies for a variable resistance if the speed is kept constant, or for a variable speed if the resistance is kept constant.

The Figs. 10, 11, and 12 show test results on a 30-H.P. 500-volt 25-period slip-ring motor for different excitations, and they show near enough the same general appearance as the theoretical curve of Fig. 9. In every figure three curves are drawn representing torque and three curves representing rotor current. The full drawn line A corresponds to direct-current excitation in the stator of 50 amperes (one terminal connected to positive, the two others in parallel to negative). The dotted B and chain dotted C curves correspond to excitations of 36 and 25 amperes respectively.

The motor would give with a 3-phase current of 500 volts, 36 amperes, a torque of 225 ft.-lbs. at 705 revs. per minute with a rotor resistance as shown in Fig. 10, and the rotor current would be equal to 52 amperes. The resistance per phase in Fig. 10 is approximately 0·3 ohm; in Fig. 11 approximately 0·6 ohm; in Fig. 12 approximately 1 ohm.

As long as we work with small direct-current excitation, which

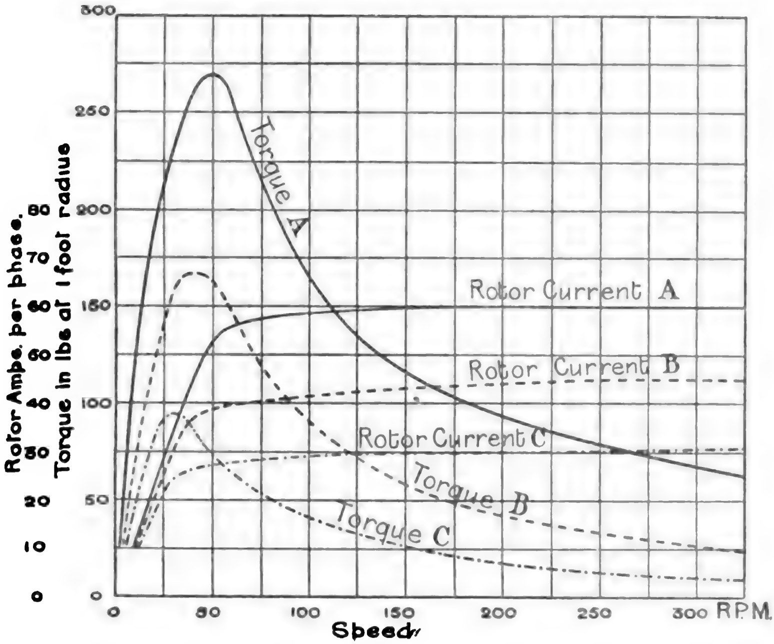

Rotor Amps. per phase.
Torque in lbs at 1 foot radius
Torque A
Rotor Current A
Rotor Current B
Rotor Current C
Torque B
Torque C
Speed
RPM.

FIG. 10.

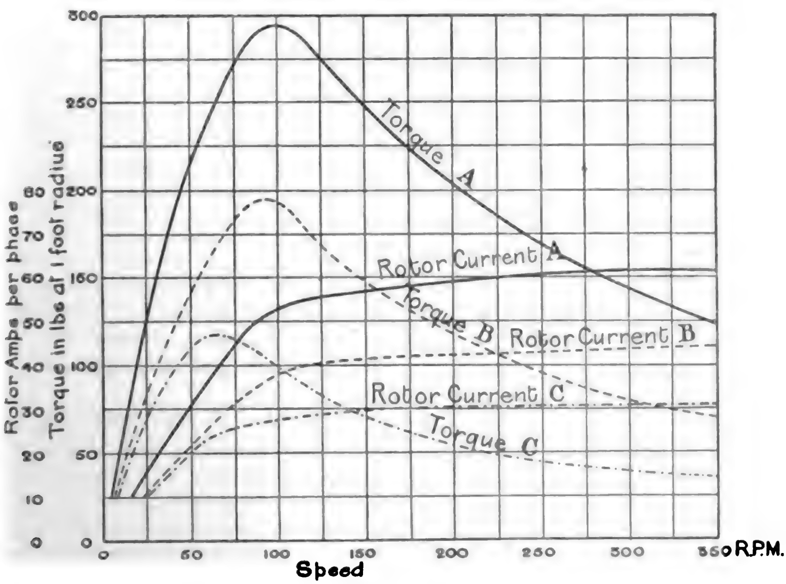

Rotor Amps per phase
Torque in lbs at 1 foot radius
Torque A
Rotor Current A
Torque B
Rotor Current B
Rotor Current C
Torque C
Speed
R.P.M.

FIG. 11.

could not saturate the field, the torque for a given speed and resistance will be in proportion to the square of the direct-current exciting current, because the field O B as well as the armature current B A (Fig. 6) are in proportion to the primary current O A. When, however, O A is far above the value which could give a saturated field, then we have only to consider the variation of armature current A B for the maximum torque, because the field no longer increases with increasing ampere-turns. The fact that for constant resistance the speed at which the maximum torque is obtained (Figs. 10 to 12) is slightly increased with increased excitation, is also caused by the limits of saturation. With high exciting current the resultant field does not grow in proportion

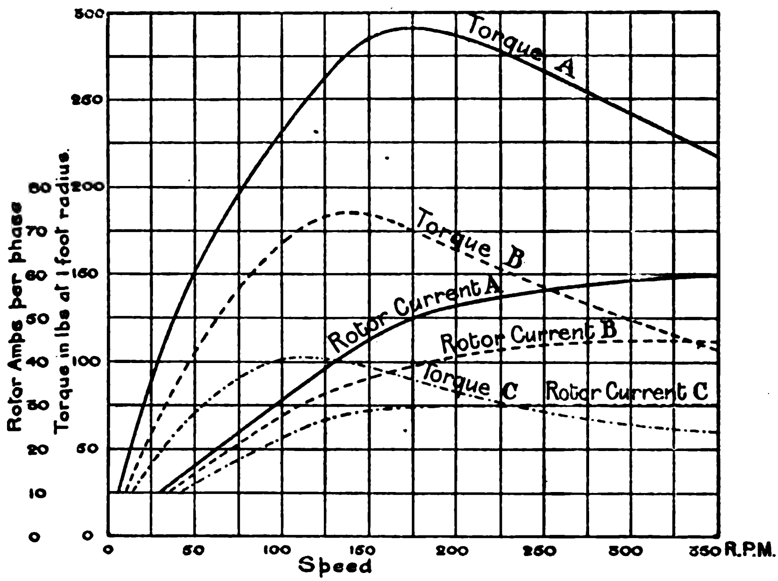


FIG. 12.

to the resulting ampere-turns, and therefore the maximum torque is reached with a comparatively higher rotor current. The curve representing the maximum torque dependent on the direct-current excitation is at first nearly a parabola (Fig. 13) which gradually approaches a straight line.

We see that the relation between torque and direct-current excitation is a simple one, as the torque always increases with increased excitation, whatever the momentary frequency may be, whereas the relation between torque and resistance is a very complex one. For a decrease of resistance the torque might be increased or decreased, dependent upon the momentary speed. Therefore, it would not be very safe to use the variable resistance of the starting controller for braking purposes, as the driver might easily overshoot the mark in

trying to make the brake more effective, and then he would not be able to stop the load. It would, however, be possible to change the resistance automatically in proportion to the frequency of the rotor currents.*

For a constant excitation and a constant resistance in the armature there always exists, as the figures show, a critical speed up to which

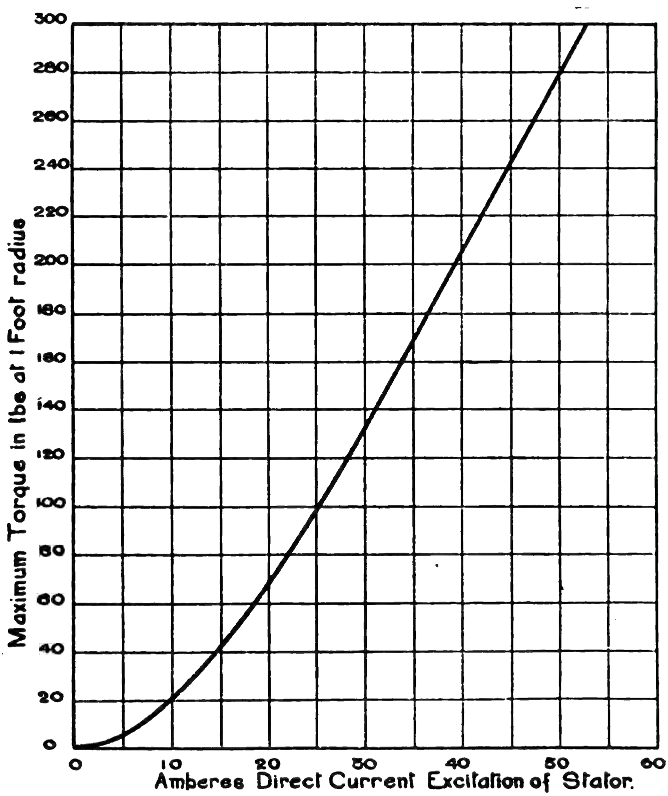


FIG. 13.

the torque increases and after which the torque goes down with increased speed. If we make the exciting current and the resistance high enough, we can easily ensure that the brake torque wanted is well below the obtainable maximum torque, and that the speed wanted is well below the critical speed; say, for instance, like M in Fig. 14. In this case the machine when started and driven by the load, the rotor connected to the resistance will attain a speed which is repre-

* Patent applied for.

sented by the abscissa of the point M in Fig. 14. The load can be lowered with the certainty that the speed will not be exceeded. For stopping, mechanical brakes would be applied.

If the motor is allowed to come to rest with full direct-current excitation on the stator, then, of course, no demagnetising effect of the armature can exist, and the enormous number of ampere-turns will create the strongest possible field in the motor. This must be carefully considered in dimensioning the mechanical parts of the motor, for any dissymmetry in the air-gap may produce a very heavy unbalanced pull, and the air-gap of an induction motor being necessarily small, there would be in large slow-speed motors the danger of the rotor pulling over before coming to rest.

This kind of brake requires a supply of direct current, which will necessitate in many cases the use of a small special motor-generator.

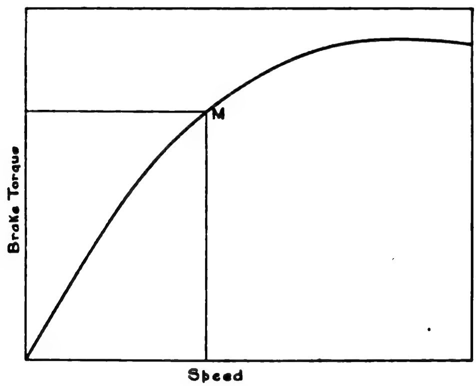


FIG. 14.

If it is required, in cases of the supply failing, to lower the load without being dependent on the mechanical brakes alone, it will also be necessary either to use a flywheel for the motor-generator or a small accumulator.

In general the curves, representing the relation between torque and speed, have a similar shape to the curves representing the relation between torque and slip in an induction motor working as a motor. There is only a gradual difference, because the curves of the motor are, as a rule, taken for constant alternating voltage on the stator winding, and therefore the stator current increases with increased rotor current. The reduction of the field is mainly due to the leakage. Here, on the other hand, the stator current is kept constant, and therefore, as soon as the rotor current grows above certain limits, the value of the resultant field diminishes rapidly.

We can say that for full-load direct-current excitation, the resultant field at a speed far below the critical speed is much stronger, and at a

speed above the critical speed, much weaker than that of an alternating-current motor working as such.

Eddy-current Brake.—Using the motor itself as a brake with direct-current excitation renders it impossible to use, at the same time, the combined effort of the brake and the motor, say, working with counter-current, and it requires some special switching arrangement for stator as well as rotor. The stator winding must be connected to a controller which allows three different connections: (1) Alternating busbars, forward movement; (2) alternating busbars, backward movement; (3) direct-current busbars for braking. Also for the rotor, if ordinarily a liquid starter is used for motoring, a switching arrangement will be necessary to throw a metallic braking resistance on to the slip-rings.

It is sometimes desirable to provide a special electric brake independent of the motor, just as it is usual in tramcars to provide, besides the motor which can be used either with counter-current or as a dynamic brake, also other brakes energised by electric current.

The eddy-current brake has often been used as a testing instrument to determine the output of motors and engines. It has been used also for electric cranes to allow of very soft and smooth working. Its application for very large winding engines, which are required under certain circumstances to lower unbalanced loads consisting of men for several hours at a reduced speed, which should never be exceeded for safety purposes, was first (as far as my knowledge goes) recommended by Mr. G. K. Chambers in Johannesburg, and very large apparatus of this description is now under construction.

Smaller forms of eddy-current brakes, fitted with copper discs and used for the testing of smaller motors, have been described by various authors, for instance, in a very complete essay by Morris and Lister.* Eddy-current brakes with iron armatures have been made by Ricter and Dettmar, who also used such a brake consisting of a simple magnet acting on the rim of a flywheel in order to produce artificial load on gas engines to facilitate the paralleling of alternators to busbars.

From the test curves published for eddy-current brakes with copper discs,† and from experiments made by myself on eddy-current brakes with cast-iron armatures,‡ I believe that an essential difference exists between the two. In the brakes as described by Morris and Lister, at first for constant excitation, the torque increases with the speed, but falls after a critical speed is reached. The diagrams have the same shape as Figs. 9 to 12 of this paper, and this is not astonishing, for an eddy-current brake with a copper winding on a steel armature represents the same problem as the alternating-current motor with direct-current excitation on the stator.

An eddy-current brake like this, used for winding engines, would

* *Journal of the Institution of Electrical Engineers*, vol. 35, p. 445, 1905.

† Morris and Lister, *Journal of the Institution of Electrical Engineers*, vol. 35, p. 445, 1905; also Feussner, *Elektrotechnische Zeitschrift*, vol. 22, p. 608, 1901.

‡ *Zeitschrift für Elektrotechnik*, vol. 20, p. 353, 1901.

have very serious disadvantages, at least, if the critical speed could not be shifted to a very high value. Morris and Lister's curve now shows the critical speed of their particular brake already at a speed corresponding to a frequency of approximately 35 to 40 cycles per second (8-pole brake approximately 500 to 600 revs. per minute).

In my article of 1902, mentioned above, I have already stated that with eddy-current brakes with cast-iron armature I was never able to find a reduction in torque with increase in speed, but, on the contrary, a steady increase. The power absorbed by the brake increases at first nearly in proportion to the square of the speed, and even with high

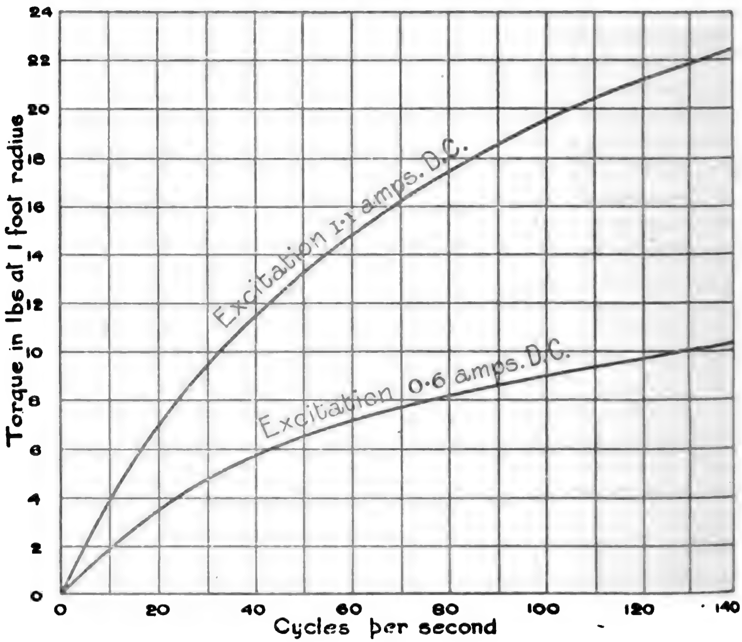


FIG. 15.

frequencies it is still more than proportional to the speed, even up to a frequency of the brake armature current as high as 130 cycles per second (field of 12 poles, speed 1,300 revs. per minute). Fig. 15 shows the steadily increasing torque for two different exciting currents.

Also in apparatus built more recently, I have always found this experience confirmed, and since for practical use this quality is of the greatest importance, the eddy-current brakes to be used in connection with winding engines were made with cast-iron armatures.

The cast-iron armature has, besides great simplicity, rigidity and cheapness, the advantage that the specific resistance of the material is approximately 40 times greater than that of warm copper. As, how-

ever, in eddy-current brakes, the section of the cast iron is very much greater than the aggregate section of copper windings used in armatures, the different behaviour of the brakes cannot be explained by the increased specific resistance only. My explanation is, that the virtual resistance of the cast-iron armature cannot be considered as a constant value, but that it increases with increased periodicity.

The cast-iron armature represents the armature of an alternator with an infinite number of phases, each one short-circuited in itself, although not of negligible resistance. We can assume, however, with certainty that starting from a comparatively low speed the armature ampere-turns will be, just as in Fig. 8, not very different from the primary field ampere-turns, and therefore the total number of ampere-turns cannot increase much with increasing speed. This, therefore, could not account for the observed increase in absorbed power. The power absorbed is made up of three components: friction and windage, which are practically negligible; the C^2R losses of the eddy currents, and the hysteresis losses of the cast-iron armature. In an ordinary short-circuited armature the hysteresis losses would be reduced with increased speed, for although the periodicity is increased, the resultant field falls more than in inverse proportion. In an ordinary short-circuited armature with defined path for the current, the C^2R losses also do not rise appreciably after a certain speed is reached. Here, however, I believe that for low speeds the flux penetrates the whole depth of the cast-iron armature, and that with increased speed, and therefore increased voltage per inch axial length, the current density near the surface increases, and that this surface current opposed to the primary flux shields the deeper parts of the armature, so that fewer and fewer lines of force penetrate and the currents crowd more and more on the skin of the armature. Therefore, with increasing periodicity, the resistance of the eddy-current path increases, and this also has the effect that the resultant flux does not tend to fall off, since in order to maintain the current with the increased resistance, a higher E.M.F. is required. Of course, owing to the crowding of the magnetic lines on the surface, the hysteresis will be increased if the total flux is not reduced with increased speed, for considering that hysteresis is not simply proportional to the induction, but to its 1·6th power, every uneven distribution of the induction must needs have the effect of increasing the hysteresis, and also, of course, the increase in frequency means increased losses. But in general, I do not believe that the hysteresis losses are the most important even at high frequencies.

If we assume that windage and hysteresis losses can be neglected, then the observed fact that not only the absorbed power, but even the torque increases with increased frequency, would give us a basis for our theory already expressed above.

1. The volume of current in the armature remaining practically constant above a certain speed, there is no other explanation for the increased power consumption than the increase in apparent resistance.

2. The volume of current remaining practically constant, there is no other explanation for the increased torque than an increase of working flux, and not a decrease as usual.

Assuming that the eddy currents are only skin deep (the word "skin" taken in a very wide sense), I figured out, from test observations on different apparatus, built during the last ten years, the depth of the working skin. The calculation is a bit rough, but it will be sufficient for the comparison of different apparatus, and also for calculating the performance of newly designed apparatus.

I assume that, under each pole, currents will flow, the aggregate of which is nearly equal to the ampere-turns of the said pole. Considering that the field winding is a coil winding, each turn surrounding the whole pole, whereas the armature currents are distributed on the surface, the latter would have to represent a bigger aggregate if their value were allowed to grow till they completely neutralised the field ampere-turns. If, therefore, we accept them as equal, the error will not be very great. We assume that they are confined to a part of the surface equal to the peripheral dimension of the pole plus a certain fringe. The currents will change their direction before they reach the centre of the pole, because the cross-magnetising component of the armature reaction reverses the polarity of the leading pole-tip. That is to say, a pole which by its field coil is so excited that with stationary armature it represents a north pole, with an average value of, say, 10,000 C.G.S. lines per square centimetre, will, with the eddy-current brake rotating, show south magnetism in the leading pole-tip, north magnetism in the greater part of the pole. The average value will perhaps be 2,000 lines of north magnetism.

If we assume that the armature of the eddy-current brake is wider than the field poles, the distribution of the currents will be similar to that in Fig. 16—that is, we shall have currents flowing similar to those in a proper single-phase drum winding with concentric end connections. If the armature is not wider than the pole-shoes, we can imagine that the end connections are bent down, and that the current flows at the front end of the rim from one part of the path to the other. We may approximate for our calculation the average length L of the current path. If we now call R the resistance of the skin, viz., of a straight current conductor of a width b, an unknown depth x, and a length L, and if we, in order to simplify calculations, assume that the number of ampere wires are equally distributed along the width b, and represent *in toto* $2ni$ ampere wires (ni being the number of ampere-turns per pole), and if it be observed that for the whole brake with $2p$ poles the power consumption in watts after deduction of losses for friction and windage is W, then we have the simple equation—

$$C^2R = \frac{W}{2p},$$

$$(2\,ni)^2 \times R = \frac{W}{2p},$$

and this will give for the observed values of excitation and frequency the depth x of the current-carrying skin.

The eddy-current brakes as used in connection with large hoisting engines are able to deal with continuous service, that is to say, with continuous trips of unbalanced loads of men or material from the surface to the bottom of the pit, and it is possible to regulate the speed without use of the mechanical brake down to a very low value. The field is excited from direct-current busbars which are fed by a motor-generator and on which a storage battery is floating; therefore the brake is also available in case of failure of the main supply current, and in such cases the excitation is switched in automatically.

The eddy-current brake in another form can be used to make the Ward-Leonard braking method also available if the Ward-Leonard motor-generator or the engine driving such generator has a comparatively small flywheel which for lowering of the load during a long trip would speed up dangerously. In such cases it will be sufficient to fit a stationary pole of small dimensions opposite the flywheel rim and

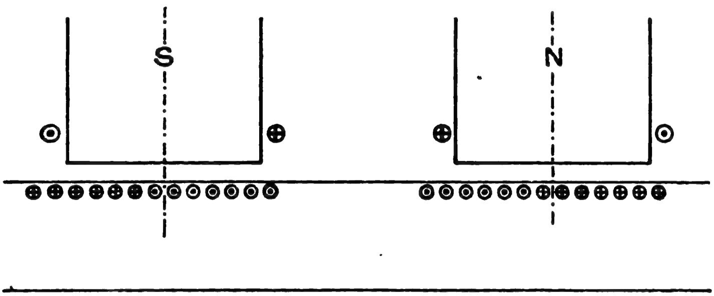


FIG. 16.

so induce eddy currents in the flywheel which consume the power supplied into the flywheel set.

I have confined myself in this paper to merely one question in the great chapter of electric winding engines which represents now, and will represent more with every coming day, one of the most important chapters of the application of electrical power for industrial purposes.

It would be futile to ask which of the systems described is the best system of electric control. The answer might be in favour of any one of the systems according to the circumstances of the case. In one case, the greatest importance might be attributed to the lowest possible power consumption, and if the starting periods and the braking periods and the periods of trips with reduced speed are of long duration, the Ward-Leonard system might prove the most efficient one. With different starting and running conditions the simple alternating-current motor system might be the most efficient in power consumption, and in other cases it might be preferred on account of its lower initial costs, even if, owing to the given conditions, the power consumption for the

shaft-horse-power works out higher. The power consumption will be of greater importance the higher the price of the kilowatt-hour in the particular case, and will, therefore, depend upon the local price of fuel and labour. As to the question whether the current consumption or the capital expenditure should be kept low, it will prove a decisive factor whether the shaft in question is intended to be worked for many years, or whether the working will cease presumably after a few years' time.

If power is taken from a supply company, the selection of the system, and the question whether equalising apparatus should or should not be used will greatly depend upon the method of charging for the current consumption. If current is charged on a flat-rate basis, an equaliser would, in general, be out of place, because it not only increases the initial costs, but also, owing to the inevitable losses, the total current consumption. A charge on the maximum demand system, on the other hand, will turn the balance in favour of equaliser systems. The question also whether any inducement is offered to the power consumer for a good power factor might turn the balance in a given case from the direct-coupled slow-speed alternating-current winding motor to the Ward-Leonard system with high-speed motor-generator. Safety apparatus which, in one case, due to the local conditions and regularity of the supply, would seem an unnecessary luxury, will be of vital importance in other cases.

So each of the systems has its own merits which will call it to the front according to the circumstances of the case.

Discussion before the Manchester Local Section.

Mr. Peck.

Mr. J. S. Peck: The subject of the braking of induction motors is of special interest. At first sight it would appear that by exciting the primary of an induction motor with direct current so as to turn it into an alternating-current generator, and by varying the resistance in the secondary circuit we could obtain almost any desired braking effect. But the author points out the difficulties in changing the connections, the magnetic stresses between stator and rotor, and, most serious of all, the fact that for each speed a certain definite secondary resistance is required for maximum braking effect. On account of this last feature it would always be difficult for the driver to know whether he should increase or decrease the secondary resistance in order to reduce the motor speed. Consequently there would be danger of the motor reaching an excessive speed, with perhaps serious consequences. It is to be hoped, however, that the scheme hinted at by the author for indicating or fixing automatically the proper resistance for any speed may be developed further. With the usual alternating-current winding engine two methods of braking are available: (1) mechanically by means of the brake blocks, and (2) electrically by means of counter current. Also in lowering it is possible to let the motor run above synchronism, and so return power to the line; but this method is not

available for lowering at slow speed or for stopping the motor. Where the motor is used as a generator by exciting the stator with direct current it is, of course, not possible to brake with counter current while the motor is generating, which is an objection to that method. With the eddy-current brake, or with any other type of external brake, such as a water brake, it is possible to use the mechanical brake, counter current, and the external brake simultaneously. Also, the external brake gives a highly satisfactory method of lowering at reduced speed. Although an eddy-current brake for a large slow-speed motor is an expensive machine, and the inertia of its rotating part adds appreciably to the power required for acceleration and retardation, there seems to be a demand for it, and under certain circumstances its use is quite justifiable. Mr. Peck.

Mr. W. CRAMP: The subject dealt with by the author is one which is bound to come up more and more often as the electrical industry advances, but as only specialists are really capable of criticising the paper, I must be content to ask the author for some explanation of points that do not seem clear. On page 431 Dr. Rosenberg refers to commutator motors as being less efficient than other motors. Yet to obtain the effect of braking he does not hesitate to recommend the provision of a special rotary converter with a commutator. It is perfectly true, of course, that commutators cause trouble, but surely it is as reasonable to have the commutator on the motor as to introduce a special rotary converter in order to produce braking current. It seems to me that if the commutator is the only objection, then it is one that fails in view of the fact that it is common to most of the other systems that the author has mentioned. For the purposes discussed in this paper there is the possibility of employing a system which Dr. Rosenberg has not mentioned. I should like to suggest to him the use of an induction motor with a variable number of poles. The only objection to the use of the induction motor as a brake is that without counter current it is only useful for speeds a little over synchronism; but if it were so arranged as to have the number of poles changed it might be used as a brake down to the speed corresponding to the largest possible number of poles; or suppose the actual winding of the motor were arranged so that it could be connected in cascade like the Hunt motor, would not this enable perfect control to be obtained when running as a motor, with a very wide range of regenerative braking? It seems to me that this ought to be possible up to a reasonable number of poles. Later on in the paper, Dr. Rosenberg refers to the shunt motor as being the only type of direct-current machine suitable for this sort of work. I would like to know why the compound motor should not be used, and whether it is not possible to cut out the shunt and use the motor as a series generator for braking purposes, very much as with ordinary tramcars? On page 440 are given two methods of producing a field from a 3-phase winding by means of continuous current. I would like to suggest that a third method is possible—viz., by exciting one phase only. On pages 441 and 442 the Mr. Cramp.

Mr. Cramp. author goes a little further into the very interesting method of braking by supplying the stator of an induction motor with continuous current. It may interest him to hear that before the British Association in 1904 a paper was read by W. Cramp,* in which a method was given of testing an induction motor excited by continuous current and driven by another machine at a speed corresponding to that of slip. This set of conditions is almost similar to that which the author makes use of in his brake. Again, in connection with the same problem he has referred to the very small value of the power which would be required for exciting the field of induction motors, and suggests that a rotary converter be used to produce the exciting current. Suppose that a rotary converter is not adopted, but that the exciter circuit of the main alternators be used for this purpose, the ordinary exciting pressure for such alternators is probably 60, 80, or 100 volts. The energy that would then be wasted in exciting the motor would be far from small, for though the potential difference across the stator itself might be small, a large resistance would have to be used with it, so that the energy lost in the resistance would be very considerable. The author also says on page 444: "As long as we work with small direct-current excitation, which could not saturate the field, the torque for a given speed and resistance will be in proportion to the square of the direct-current exciting current." That statement is not quite true, I think. It neglects armature reaction. The method mentioned on page 449 of using a cast-iron eddy-current brake seems to me extremely interesting. It is a little puzzling to understand why the torque should constantly increase with increasing speed. It would seem that Dr. Rosenberg's explanation is the right one, for if the resistance of the mean path of the current be only a little increased the effect is large. There is, in fact, a threefold result. First, the current is prevented from rising, so that the induced ampere-turns do not change much. Secondly, the relative phase of these ampere-turns with respect to the inducing field is changed so as to minimise their reactive effect; and thirdly, this very phase-change will tend to increase the required torque. Indeed, it is plainly possible to calculate what change in the resistance of the path of these currents must have taken place to account for the result observed.

Mr. Frith. Mr. J. FRITH: I shall confine my remarks to the question of eddy-current brakes, as I have had some experience with these. I have used the form with an external iron wheel and an alternator field for ordinary test work to absorb the load of motors, and find it a very convenient and flexible appliance. I, too, have found that the torque increases with the speed. I take it that the path of the eddy currents is so undefined that their armature reaction on the field magnets is only very slight. To direct the eddy currents I have tried slotting the iron and putting in a copper squirrel-cage winding in good electrical contact throughout with the iron, but have had better results from employing the copper end-rings only without the axial bars; these

* "Report of the British Association, 1904, p. 687

latter seem to offer an inducement to the eddies to travel right across the face of the brake. I have used this method of braking small induction motors, using one phase in series with the other two in parallel to carry the direct current. Of course the difficulty is that the effect decreases as the motor is brought to rest. Mr. Frith.

Mr. S. J. WATSON: I have been thinking what the effect would be on a generating station supposing there were about a dozen collieries connected up without any equalising load arrangement, and that they all got into synchronism. I understand that each would have a maximum load of about 1,500 k.w., so that if they happened to get into step there would be "peaks" of 18,000 k.w., and the complete cycle of no-load to 18,000 k.w. would occupy about 1½ minutes. It would be a splendid method of testing governors to see whether the regulations of the Board of Trade in regard to frequency could be complied with; and as the variation in load would undoubtedly be accompanied by a considerable charge in the power factor, the voltage regulating of the alternators would also be well tested. Mr. Watson.

Mr. T. FERGUSON: It is most important to consider carefully the subject of safe and efficient braking methods before giving preference to any one system of control for a given electric winding proposition. Engineers, when passing from steam to electric winding, sometimes neglect to give due consideration to the braking features of the problem, and concentrate it rather on the load-lifting features. The latter might, it is true, be the dominating factor in steam-winding propositions, but it is not necessarily so in electric winding—in fact, the final choice of the system of electric control might conceivably be determined by the question of efficient and safe breaking when lowering loads. When considering the various available systems of braking treated by Dr. Rosenberg in his paper, the most obvious method, and one which would appeal to the steam user, would be braking by counter current, although it might not be a good commercial proposition when lowering loads for a considerable time. In this case the Ward-Leonard system might be preferable. The ideal arrangement would be to have a separate winding plant for lowering and raising men into and out of the mine; but as a rule it would not be practicable to provide such a plant. I have recently come across a proposition for installing in the up-cast or ventilation shaft of the mine a hoist for men, but have not heard that it has been adopted, and there certainly might be some consequent inconvenience. Of course, the cage has to be made a cage in every sense of the word, the top and bottom being made of grids or bars so as to prevent obstruction to the ventilation. In considering the eddy-current brake for lowering loads, it must be granted that it offers considerable safety and ease of manipulation. For example, if a tail or balance rope is used between the cages, and the static torque thus made uniform throughout the wind, it is an easy matter to switch on the exciting current to the eddy-current brake and leave it on, and then simply operate the main control lever in a natural manner, starting the load downwards, if necessary, Mr. Ferguson.

Mr. Ferguson. by a short application of current, then bringing the control lever back to the off position, when the load will descend at a uniform rate under the action of the eddy-current brake; then, finally, pulling the control lever backwards so as to apply counter current and thus bring the load to rest.

Mr. Mallinson. Mr. A. B. MALLINSON: I consider that colliery people will be rather apt to condemn large eddy-current brakes. When electric power is considered for winding deep shafts, one of the first requirements is that power must be returned to the line wherever possible. The electric winders which I have seen in operation so far in this country are merely toys in comparison with what is daily being done by the high-class steam winders at the Powell Duffryn and other large pits. When electric winders of similar duty are put to work, I think the losses between winds (due to the running flywheel set) would be so reduced that direct-current winders with a flywheel converter would show an overall efficiency better than would be obtained with alternating-current winding equipments. I would ask Dr. Rosenberg whether he has come across any case where power is actually returned to an outside supply company's mains when braking the motor dynamically.

Mr. Stevenson. Mr. A. F. STEVENSON: Referring to a question by Mr. Mallinson, I have known of a case in which power was being returned to a power company's mains, and as they looked upon it as bad business they put a ratchet on the meter to prevent its going backward. I think that we need only consider winding plants (at collieries) supplied from power-supply mains, the capital expenditure involved making it almost impossible to get collieries to take it up otherwise. In fact, lack of capital is holding up an enormous amount of work still to be done in replacing extremely inefficient air and steam driving underground, where the saving would be very great. The rheostatic method of control applied to a 3-phase motor on the power-supply mains appeals to one as the most suitable for colliery conditions, the checking and adjusting of the cage position being done by counter current in exactly the same manner as steam is used at present.

Mr. Shaw. Mr. W. B. SHAW: One method of braking referred to in the paper is that of checking by reversing, and I would like to ask Dr. Rosenberg exactly what happened when the main switch of a 3-phase motor running at normal speed was rapidly switched over to the reverse position. I have found in the case of a small haulage motor that the current rose to a high value even if full resistance were switched into the rotor circuit in the interval between opening the main switch and closing it on the reverse position. With regard to the general question of braking, it seems to me that unless energy were returned to the line the only argument in favour of electric braking is that it is electric, and perhaps would lend itself to lighter and more easily regulated control apparatus than the mechanical friction brake now in use with steam winders. I think colliery managers would prefer to put up with the friction brake in which he felt confidence rather than go to the expense of an electric

brake, especially if it was also proposed to instal a friction brake as a standby. Mr. Shaw.

Dr. D. K. MORRIS (*communicated*): An interesting point is raised by the author in connection with the use of separate braking devices. He mentions the fact that there exists in brakes of the eddy-current type a speed of maximum retarding torque, beyond which speed the torque diminishes. The Morris and Lister brake, as made by my firm, consists of two revolving wrought-iron discs, each faced on one side with a thin sheet of copper secured by rivets, and provided on the other with suitable cooling vanes. An approximate theory of this brake was given in the paper to which reference is made by the author, and it will be seen there that the maximum of torque is dependent only on the dimensions and excitation of the brake. But the speed at which this maximum occurs varies inversely with the thickness and conductivity of the facing of the discs. The effect of doing away with the conducting material on the iron discs and using only the iron is, as Dr. Rosenberg points out, to remove for all practical purposes the disadvantage of having a maximum of retarding effect; but, according both to our experiments and the theory, what really happens is not only that the critical speed is very high, but that the maximum torque occurring at this speed is obtained only by excessive exciting current. Brakes for testing petrol motors have frequently to be made for a speed of over 2,000 revs. per minute, and the maximum of torque must not occur within this speed (which corresponds to 133 periods on an 8-pole brake). This condition is met without difficulty by using very thin copper facing, or even by using a material of slightly less conductivity than copper, and no increase of exciting current to produce a given maximum torque is required. The eddy-current principle, if applied in the way generally adopted by us, would seem to be well adapted to give good results at a moderate outlay on winding plant of this type. Dr. Morris.

Dr. E. ROSENBERG (*in reply*): Mr. Cramp asked what objections exist against single-phase commutators being used for large winding engines, and pointed out that the aversion against the commutator does not prevent us from using a commutator exciter. The objections, of course, are not those of theoretical like or dislike, but mainly of expense and efficiency. To get good commutation in a single-phase machine, we must have very low voltage between bars, and have to build the armature for low voltage and high current, which gives, for a large output, a very expensive commutator and brush-gear. Besides, the efficiency of the single-phase motor is lower than that of either the direct-current or the 3-phase induction motor, and we have here no counterbalancing advantage as in traction work, where the simplicity and higher efficiency of the trolley line and the elimination of rotating converting apparatus gives ample compensation for the lower motor efficiency. Mr. Cramp suggested also that induction motors with devices for changing the number of poles may be used in order to allow a wide range of regenerative braking. Although it would hardly be possible to get a smooth gradual braking for any great range in Dr. Rosenberg.

Dr. Rosenberg.

this way, no doubt the pole-changing device could be used to get economical running at half-speed, and to lower men by running the motor with the double number of poles a little above synchronism. The practical objection against doing this with direct-coupled large winding motors is the great number of poles which would be required, and the deterioration in performance which such an arrangement of stator and rotor coils gives even at full speed. Consider, for instance, the case of a 50-cycle winding motor running at 60 revs. per minute. This means 100 poles, and as the diameter of the machine has to be kept within certain limits, and the air-gap cannot be made unreasonably small, this number of poles gives, from the power-factor point of view, anything but an ideal design. To design such a motor for half-speed with 200 poles would be an exceedingly difficult task. As to the suggestion of making a direct-current winding motor heavily compounded and using it for braking purposes as a series generator, I would point out that the speed of the compound motor is dependent upon the load, and this is always undesirable, but is specially objectionable in cases when the direction of the torque changes during the trip—when, for instance, there is no balance rope, and the weight of the rope works at first against and afterwards with the torque of the motor; in this case violent speed variations will occur. As to direct-current excitation of 3-phase motors, Mr. Cramp mentioned that the energy for stator excitation represents a considerable item if the current is taken from exciter busbars. This is true if we have to deal with low-voltage motors; very often, however, the stators are wound for high voltage, say 2,000 to 6,000 volts, and in this case a voltage of 110 to 220 volts would not be much in excess of the voltage required for ohmic drop on the terminals. I believe that my statement on page 444, paragraph 3 —viz., that for small excitation the torque for a given speed and resistance will be in proportion to the square of the exciting current—is quite correct, and takes due account of the armature reaction, which latter will be in proportion to the exciting current. Mr. Cramp mentioned that the eddy-current brake behaved as if there were no armature reaction. Of course, we cannot possibly assume that, but if, as I tried to explain, the currents at higher peripheral speed crowd towards the surface and shield the lower parts of the iron from lines of force entering, then we can understand that the armature reaction will not be increased with increased speed. Of course, my explanation of the eddy-current brake with cast-iron armature is open to criticism. I have tried to explain the observed facts by this theory, and a further discussion on the possibility or likelihood of this theory would be very welcome.

As to Mr. Frith's design of cast-iron brakes with copper end-rings, I would be interested to know whether this really did increase the torque for a given excitation.

Mr. Mallinson mentioned that the eddy-current brake does not allow of the power being returned to the line. That is, of course, in itself not possible with 3-phase winding motors. The question,

which is the more important—a return of power to the line, or independence from a momentary failure of line current—will be a special question in every particular case. For English coal-mines, the eddy-current brake would hardly ever be required. I have seen mines where winding of the coal and of miners is done at the same speed, and in most cases also, trips with unbalanced load are of rare occurrence. In this case the expense for the eddy-current brake would not often be justifiable. It will, however, be quite another matter if safety is the first consideration, and if the lowering of men has to be done several hours in every working shift without balancing load. It also depends upon the circumstances of each case whether it is preferable to put up with the loss of energy during the starting and braking period or with the losses in the Ilgner motor-generator extending over the whole day. Dr. Rosenberg.

Mr. Shaw asked whether the rushes of current are not too great if the motor is reversed while running at full speed. This would not happen if the controller is properly designed for this service. I have explained in my paper that for braking with counter current a larger resistance is required than for starting, and therefore liquid-starters like those illustrated in Fig. 2, if to be used for counter current, have as a rule a special sluice-gate which allows for a lower water-level for braking. Of course, a controller of an ordinary haulage motor, with only a few steps, which allowed on the first step for starting, say, twice normal current, would, if reversed with the motor running at full speed, give a rush of nearly four times the normal current, and this would certainly be objectionable.

With regard to Dr. Morris's communication, I think it would be difficult to design a brake of several hundred horse-power in a way similar to his own interesting apparatus. It is hardly feasible to do without water-cooling, and the connection of a thin copper plate to the iron armature would very likely give rise to mechanical difficulties owing to the great temperature differences encountered.

STATIC SUB-STATION DESIGN.

By P. V. HUNTER, Associate Member.

(*Paper received November* 23, 1910. *Read before the* NEWCASTLE LOCAL SECTION *January* 16, 1911.)

The importance of static sub-station design is apt to be underrated on account of its apparent simplicity, but when a systematic attempt is made to arrive at the ideal, it is surprising how complex the problem becomes. The ways in which transformers and switchgear may be arranged with relation to one another are practically infinite, and nearly every way has something to recommend it. In fact there is so much scope for originality that the designer is apt to follow ingenuity for its own sake, rather than reduce the subject to an economical association of essential principles.

It is, however, difficult to limit the issue to a number of definite considerations capable of statement as an individual problem. The subject is simply an important consideration in the design of a system of electricity supply, and cannot be looked at entirely from an isolated point of view.

Scope of Paper.—In writing this paper the author has particularly in mind the conditions met with on the North-East Coast. While this limitation does not affect the essential principles of design, which are common to all conditions, it has influenced the examples shown and they must be considered with this in view.

As it is impossible to deal with the whole question within the limits of a single paper, attention will be confined more particularly to the arrangement of buildings and plant. Considerations imposed by the supply system generally and questions of cost will not be entered into in detail. It is, of course, necessary to make some reference to them in order to record their actual influence on the problem.

Supply System.—Apart from engineering duties the design of sub-stations is materially affected by the general policy adopted throughout the supply system; that is to say, the attitude which the supply authority takes towards its responsibilities on the question of maintenance of supply, and the extent to which it is prepared to encourage business by spending money on standby plant and automatic apparatus with the object of eliminating failure of supply. In general the longer the experience and the greater the responsibilities, the more conservative is the attitude.

From the point of view of the supply system, sub-stations must be considered as switching centres for the high-tension transmission system.

It is essential therefore that the switchgear be constructed not solely to suit the sub-station plant, but to meet the conditions imposed by the magnitude of the system and future developments. An important matter in this connection is the provision of regulating apparatus for controlling the loading of individual high-tension feeders.

Cost.—The design of individual sub-stations cannot in general be settled on a minimum cost basis, as such procedure generally leads to wasted capital when further developments arise, and is attended by continual risk of breakdown involving interruptions to supply. It is,

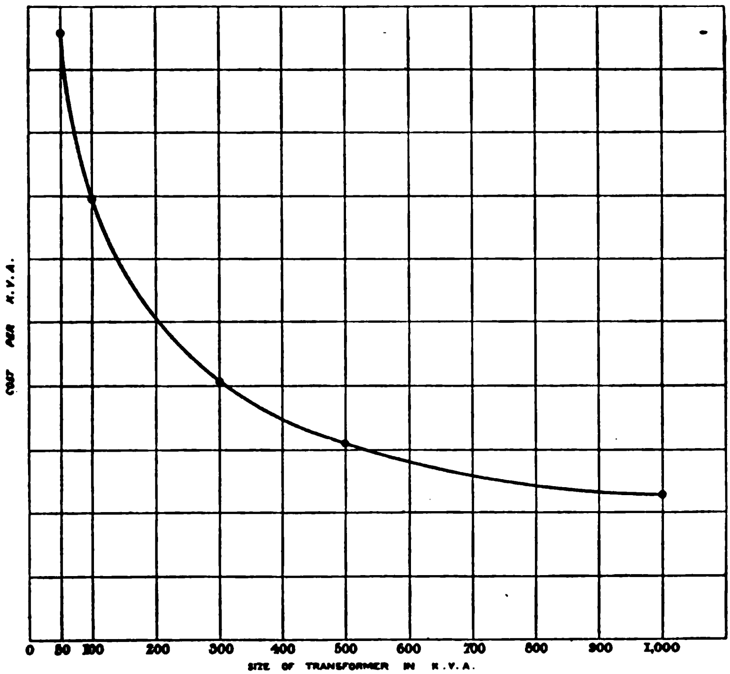


FIG. 1.—Curve showing Relation between Size of Transformer and Cost per Kilovolt-ampere.

however, useful to note one or two characteristics of the cost of the apparatus.

With naturally cooled transforming plant the minimum cost per kilovolt-ampere is reached when the size approaches 1,000 k.v.a.; up to this size there is a reduction in cost per kilovolt-ampere the larger the transformer. The rate of decrease is important, and the curve in Fig. 1 shows the cost per kilovolt-ampere plotted against size of unit for 3-phase transformers wound for 5,500/440 volts 40 cycles, and may be regarded as typical,

The cost of high-tension switch panels is practically proportional to the voltage, and more or less independent of the full-load current within working limits.

Compared with the complete equipment the cost of the building is a relatively small percentage, and the difference between two buildings therefore expressed as a percentage of the total cost is practically negligible. In fact, it is generally possible to consider buildings entirely on their engineering merits, provided care is taken to guard against redundant space.

Purpose of Building.—Having noted the conditions imposed by the main supply system, and the relative importance of cost, attention may be directed to the main problem of design.

The primary function of static sub-stations is properly to house suitable apparatus for transforming alternating currents, which apparatus consists essentially of static transformers and switchgear.

In general, the ultimate extent of the plant and the final working conditions of secondary voltage are not known at the outset. The merits of a particular design of building must therefore be judged not only by the manner in which it meets the needs of the initial apparatus, but also by its suitability for extension to meet possible future requirements. For instance, commencing with only one pressure, a further secondary pressure may be required later. Increased demand may necessitate larger or additional transforming plant, and extensions to the transmission system may mean the installation of regulators and further high-tension feeder panels. A satisfactory design must be capable of ready extension to meet these future possibilities without sacrificing essential principles of design.

Types of Sub-station.—It is convenient for the purpose of this paper to divide sub-stations into two types, namely, those containing artificially cooled transformers, and those in which the plant is cooled by natural radiation. In general, the former type is used only for large powers where the saving in capital expenditure justifies the cost of attendance. For this reason the number of such sub-stations is small. Increased output is obtained by adding similar units (as in the generating plant of a power station), and the whole problem of design is consequently considerably simplified.

In the first instance, therefore, the naturally cooled type will be considered, as the conditions are more variable and the problem more complicated.

Essential Principles of Design.—The guiding consideration in the design of static sub-stations, as in the rest of a supply system, is maintenance of supply. The attainment of this ideal is contributed to by four principles which may be regarded as essential: (1) The use of sound and properly designed apparatus; (2) the use of automatic devices for isolating faulty apparatus; (3) the maintenance of sufficient reserve of plant; (4) an arrangement preventing consequential damage and facilitating maintenance.

The first two of these items do not materially affect the general

design of building, but the others are all-important factors and require detailed consideration.

Reserve Plant.—The provision of reserve plant involves the division of the equipment into similar sections, so proportioned that in the event of the failure of one section, there will be sufficient plant left to deal with the load. In estimating the maximum load to be carried by a particular combination of sections account may be taken of the overload capacity, provided spare plant is kept available in the stores to limit the period of overload. Each spare may, of course, serve for a number of sub-station equipments.

The first difficulty which arises in this connection is the number of sections for any particular load, assuming one section as reserve. With two sections only, the capacity of the total transforming plant is 33 per cent. greater than with three sections, and at first sight it would appear that the larger the number of sections the more economical the arrangement. Actually, due to the falling cost per kilovolt-ampere with increasing size of transformer, the reverse is the case, as may be seen from the curve in Fig. 1. For a 1,000-k.v.a. load two transformers of 1,000 k.v.a. each are cheaper than three of 500 k.v.a. At the other end of the curve two 100-k.v.a. transformers are cheaper than three 50 k.v.a. Further, as the larger number of transformers require more switchgear, the balance is still more in favour of the smaller number of sections. Above 1,000 k.v.a., the balance begins to turn in favour of increasing the number of sections.

Arrangement.—The most important requirements in the arrangement of sub-stations are protection from consequential damage, and ease of maintenance. Fortunately, these two requirements are almost identical in their effect on the problem, that is to say, to a large extent arrangements made to prevent consequential damage also prevent accidents to workmen and apparatus during maintenance operations.

Consequential damage in this connection is taken to be the damage to any part of the equipment caused by breakdown of apparatus in another section. Ease of maintenance involves, in addition to mutual protection of the workmen and equipment from each other, ready and safe access to all parts of the equipment. In general, the requirements of satisfactory maintenance may be met by providing screens or guards between sections. Protection from consequential damage requires that these screens shall, in addition, be made fire and explosion proof. In practice, the most convenient form of fireproof screen is brickwork or concrete.

The initial step towards the ideal in the design of sub-stations is to adopt an ordered lay-out in which not only is the main apparatus arranged in a systematic manner, but also the various connections between apparatus are run as directly as possible without crossing, and those belonging to each section of the equipment kept entirely separate. A simple design of this kind is shown in Fig. 2, which indicates the actual arrangement of plant adopted in a small sub-station erected in 1904 containing two 100-k.v.a., air-cooled transformers.

It will be noted that no serious attempt has been made to guard against the fire risk, and to protect the workmen during maintenance operations it is necessary to use removable screens. The design is therefore suitable for small transformers of the air-cooled type only. A further objection to this arrangement for larger outputs is the amount of ground space which would be occupied. Extensions are difficult without resorting to complications, as with three sections it would be necessary to make very special provision in order to gain proper access to the middle transformer. It is desirable, therefore, for large powers, to modify the design of the building. A two-storey construction has been found to lend itself very conveniently to the aims

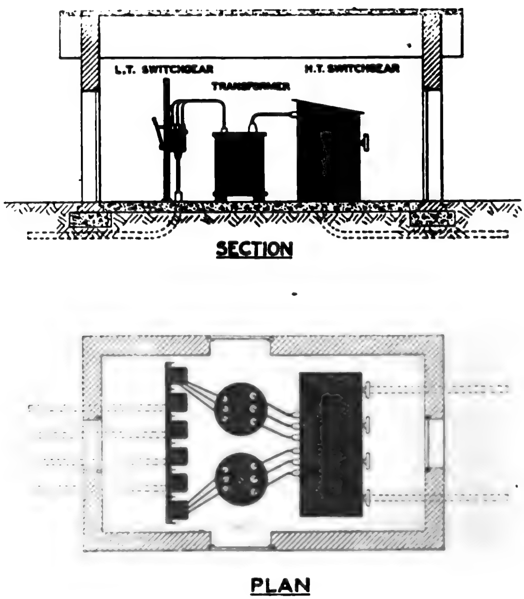


FIG. 2.

of the designer. In addition it has the advantage of reducing ground space to a minimum.

An early design of this type is shown in Fig. 3, which gives diagrammatically a sub-station built in 1904 for a maximum load of 3,000 k.v.a., with oil-cooled transformers. This arrangement disposes of the objections and difficulties noted in connection with Fig. 2.

The fire risk has been to a large extent met by placing the transformers in fireproof cubicles.

The connections between apparatus are also satisfactory from the point of view of consequential damage. Ground space has been reduced to a minimum. One disadvantage is the bunched arrange-

ment of the low-tension outgoing feeder cables, which have to be racked on the wall at the back of the low-tension switchgear and taken out of the building at the ends.

Ventilation.—A serious consideration which arises with transformers of moderately large outputs is the necessity for ventilation. Trans-

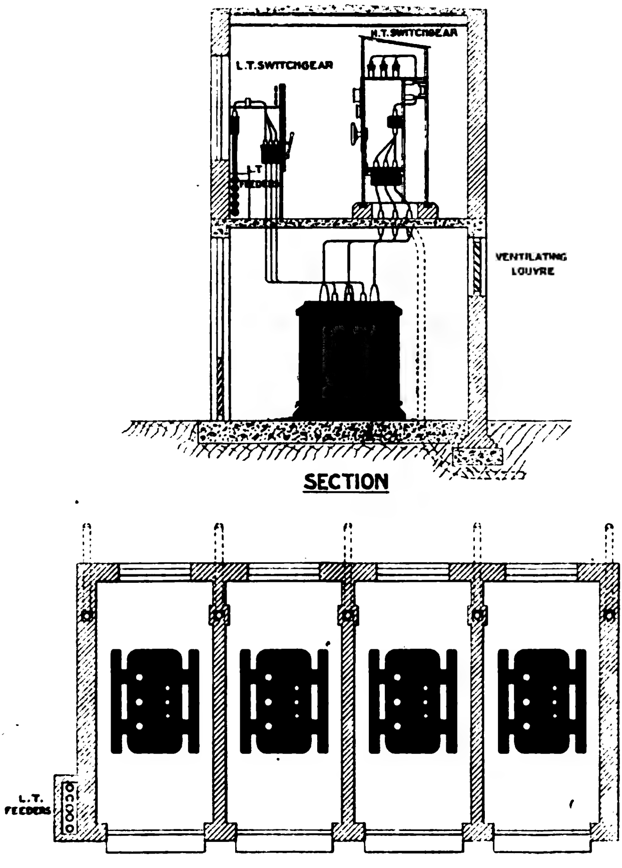
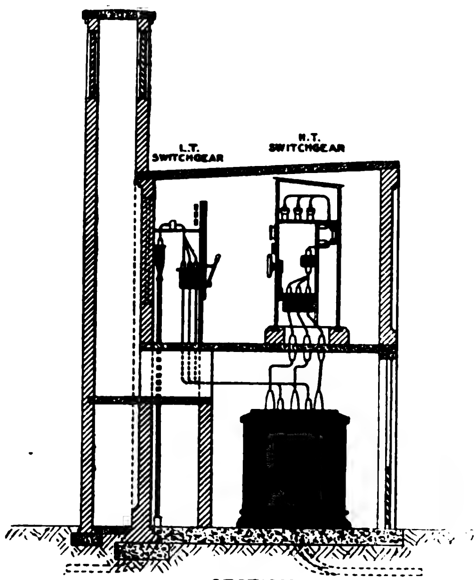


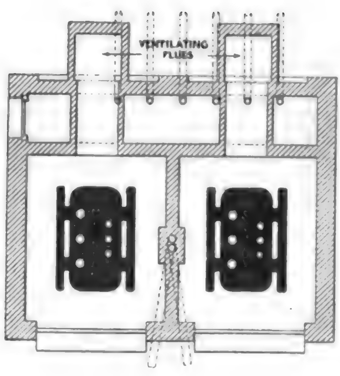
FIG. 3.

formers are designed on the assumption that the maximum temperature is determined when running in a large room with an unlimited supply of air at atmospheric temperature. This precise condition is never attainable in a sub-station, as the cost of the building would be prohibitive. Some special arrangement creating a draught is therefore necessary. The ventilating apertures in Fig. 3, although adequate, as

ventilation is ordinarily understood, do not induce a sufficient draught. Fig. 4 is an improvement in this respect. Here special ventilating flues are provided for creating a draught through the transformer



SECTION



PLAN

FIG. 4.

chamber, the air being admitted through louvres in the bottom half of the door at the front of the chamber. These flues must, of course, be calculated on the basis of the losses of the largest size of transformer which the chamber will eventually accommodate. It is important that

sheet iron or similar material should not be used for flues unless special precautions are taken to prevent loss of draught through radiation. The outgoing low-tension cables in Fig. 4 are accommodated in a chamber running the whole length of one side of the sub-station giving

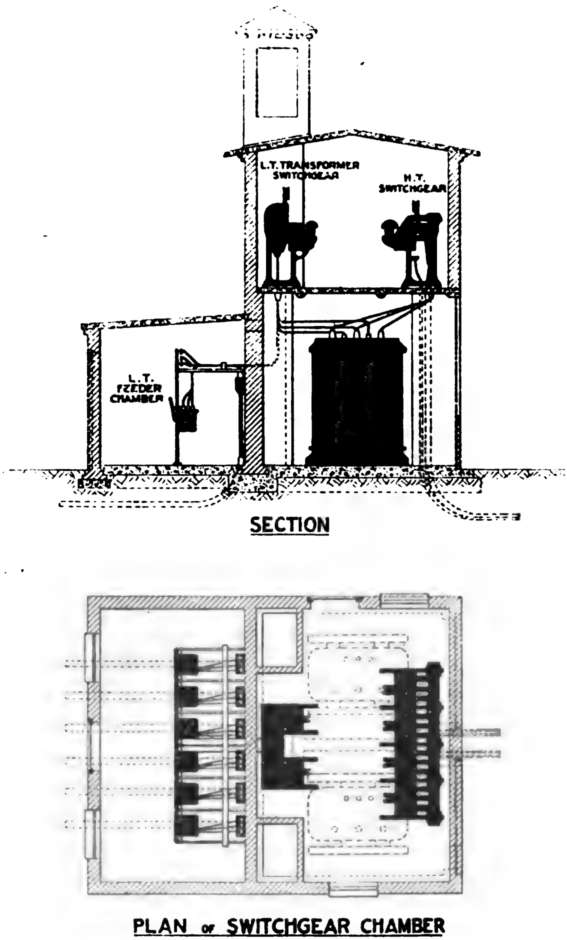


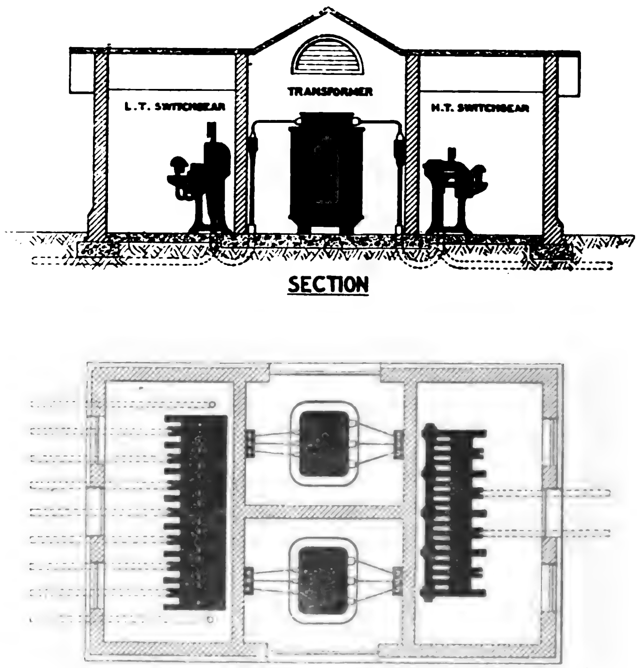
FIG. 5.

a neat and safe arrangement which avoids all reasonable risk of consequential damage.

The arrangement indicated in Fig. 5 is usually more convenient than that of Fig. 4, as the low-tension feeder switches are located in a special chamber. In the case of a sub-station on a consumer's premises

this enables him to operate these switches without entering the high-tension chamber. It also admits of the consumer using a switchboard of any particular type which may suit his convenience, without erecting it in line with the supply authority's low-tension transformer and meter panels, which will be of a certain standard type.

Size of Building.—While the sub-station shown in Fig. 5 meets the requirements of sound design assumed to be essential, before dimensions can be settled it is necessary to know the maximum size of transformer to be accommodated.



SECTION

PLAN

Fig. 6.

As pointed out on page 463, there is no economy in using transformers larger than 1,000 k.v.a. This may be considered therefore a convenient maximum size of transformer to be accommodated. In some cases, however, it may seem improbable that the load will ever reach this figure, and a reduction in the size of transformer chamber is therefore possible.

In Fig. 5 it will be found that the only reduction in size which can be made is in height of chamber, as the width and length are governed by the accommodation required for the switchgear on the first floor.

In any case the difference in dimensions of transformers in sizes between 300 and 1,000 k.v.a. is so small as to make it hardly worth while to alter the dimensions of the chamber for the smaller sizes. For small loads, however, where the ultimate demand can be accurately predicted, some modification of the design shown in Fig. 2 is suitable. As not more than two chambers will ever be required, the difficulty of building extensions is eliminated, and owing to the smaller size of transformer adequate ventilation can be arranged. Fig. 6 shows one arrangement suitable for these conditions, which has the advantage over Fig. 2 that possibility of consequential damage is reduced and ease of maintenance is obtained. A convenient distinction between Figs. 5 and 6 is to adopt the latter for loads that will never exceed 500 k.v.a.

Extensions.—Increasing load may be met in any of the designs by replacing the transformers by larger ones. With the designs shown on Figs. 3 to 5, when a maximum size of 1,000 k.v.a. is reached the number of sections is increased. Sections may be added indefinitely provided the site is suitable. Where two secondary pressures are required the arrangement shown in Fig. 5 may be extended as shown in Fig. 7.

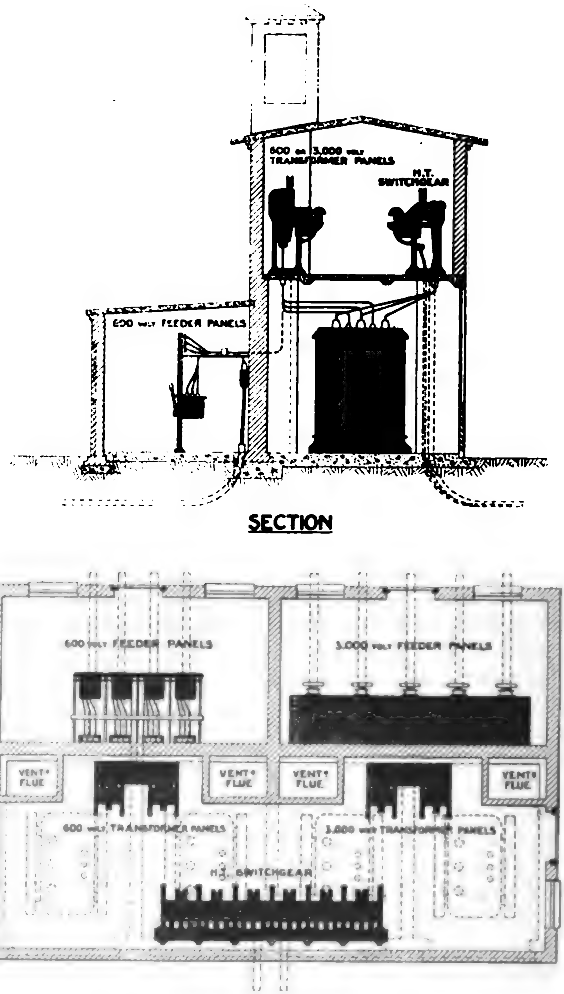
Pressure Surges.—The designs shown in the previous Figs. are intended for underground cable systems where the primary pressure does not exceed 10,000 to 12,000 volts. Under these conditions pressure surges are seldom met with (particularly if turbine-driven generating plant is used), and discharging devices have not been shown. In any case the factor of safety of the insulation of a properly constructed system for these pressures is so large that a surge to be dangerous would exceed the dissipating power of ordinary roller spark-gaps. Should serious trouble be experienced, apparatus of the electrolytic or water-jet type would be necessary, installed at points where experience shows trouble is to be expected.

With an overhead line system for a similar primary pressure it is advisable to provide horn arresters, with resistances in series to earth, for dealing with lightning discharges. Fig. 8 shows a suitable arrangement for an overhead line sub-station under these conditions.

This design also shows the low-tension transformer panels adjoining the consumers low-tension feeder panels. The arrangement is economical in buildings, but inconvenient for testing the transformer automatic cut-outs. It also requires that similar switchgear be used for the low-tension transformers and feeders.

For higher primary pressures it is generally considered advisable to provide pressure surge arresters on each feeder panel, and Fig. 9 shows an arrangement similar to Fig. 5 to meet these conditions. The arresters here shown are ordinary roller spark-gaps with resistances in series. This apparatus has a limited discharge capacity, and in Fig. 10 accommodation for electrolytic arresters is shown. This design also shows the manner in which a feeder regulator may be added.

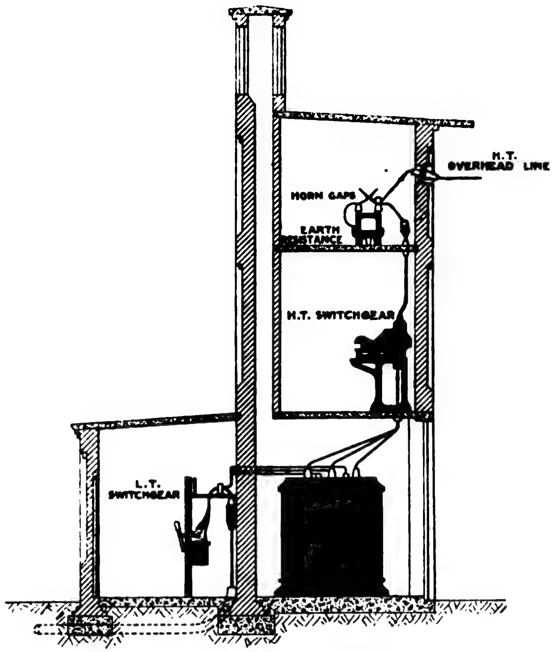
Artificially Cooled Transformer Sub-stations.—In the design of substations for artificially cooled transformers, the problem is generally



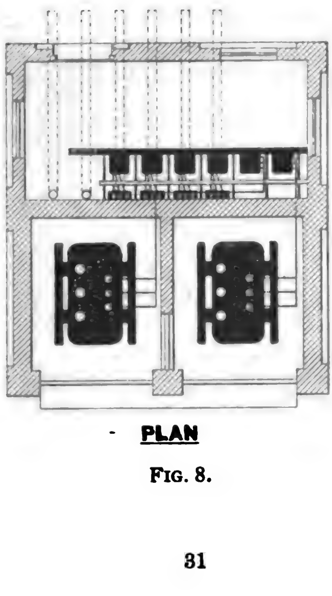
PLAN OF SWITCHGEAR FLOORS

FIG. 7.

similar to that for naturally cooled, as described above, except that the chambers may be built to suit the size of transformers installed initially, and the ventilating difficulty is eliminated.

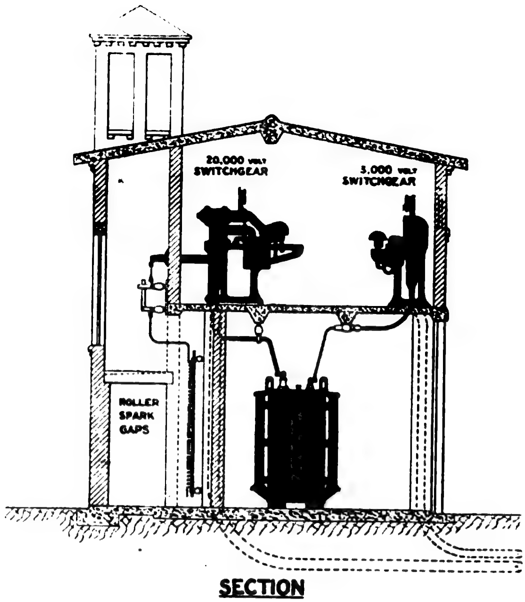


SECTION



PLAN

FIG. 8.


20,000 VOLT SWITCHGEAR
3,000 VOLT SWITCHGEAR
ROLLER SPARK GAPS
SECTION

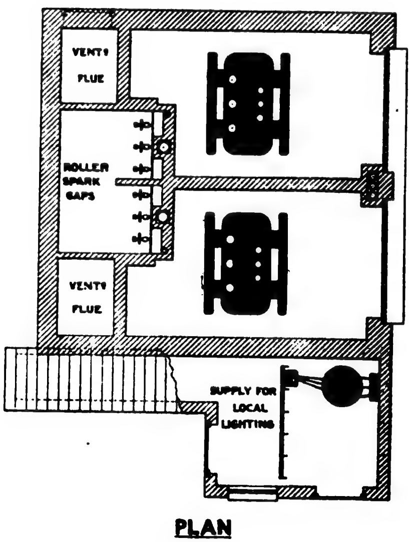
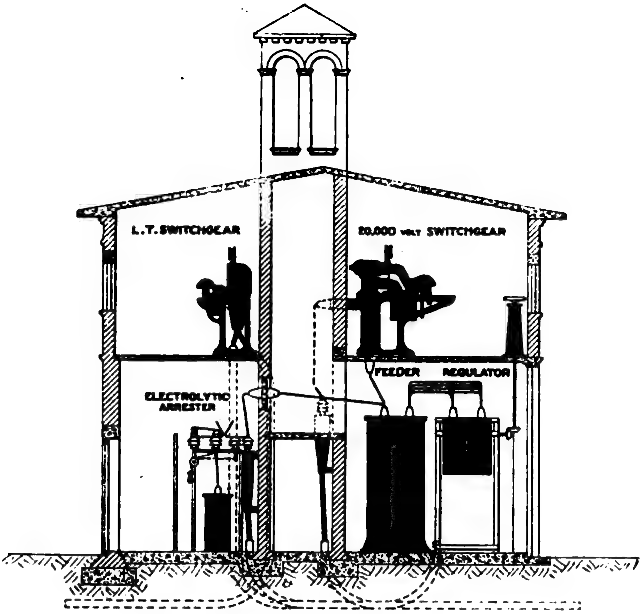

VENT
FLUE
ROLLER SPARK GAPS
VENT
FLUE
SUPPLY FOR LOCAL LIGHTING
PLAN

FIG. 9.



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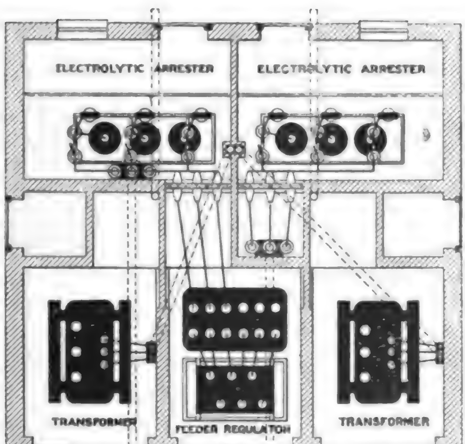
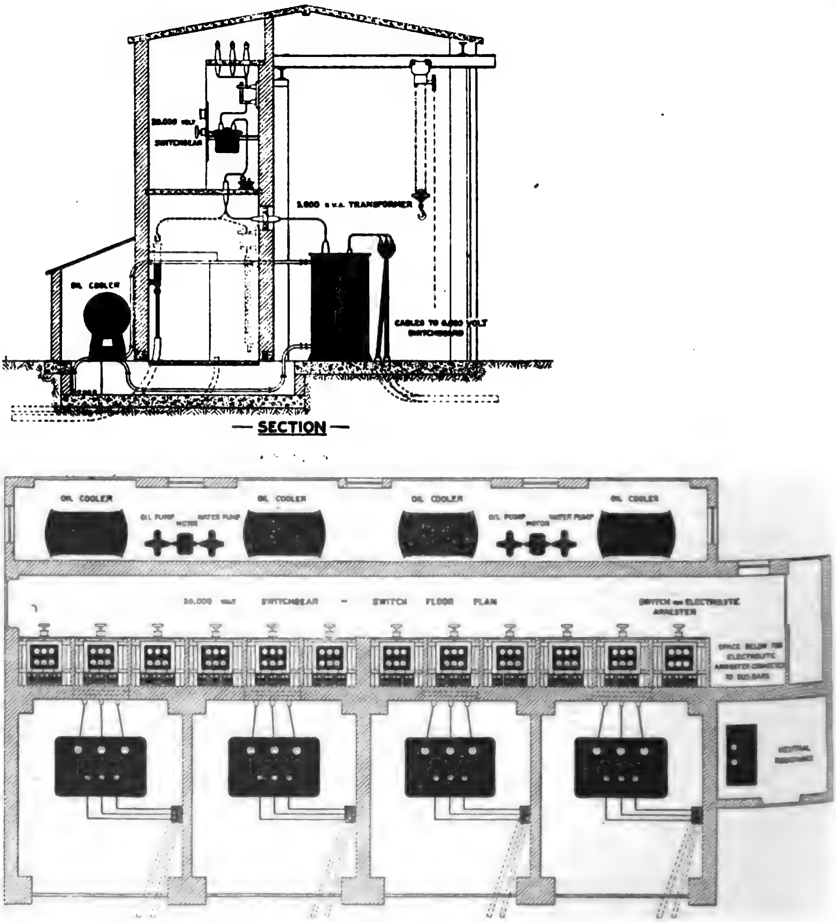


PLAN

FIG. 10.

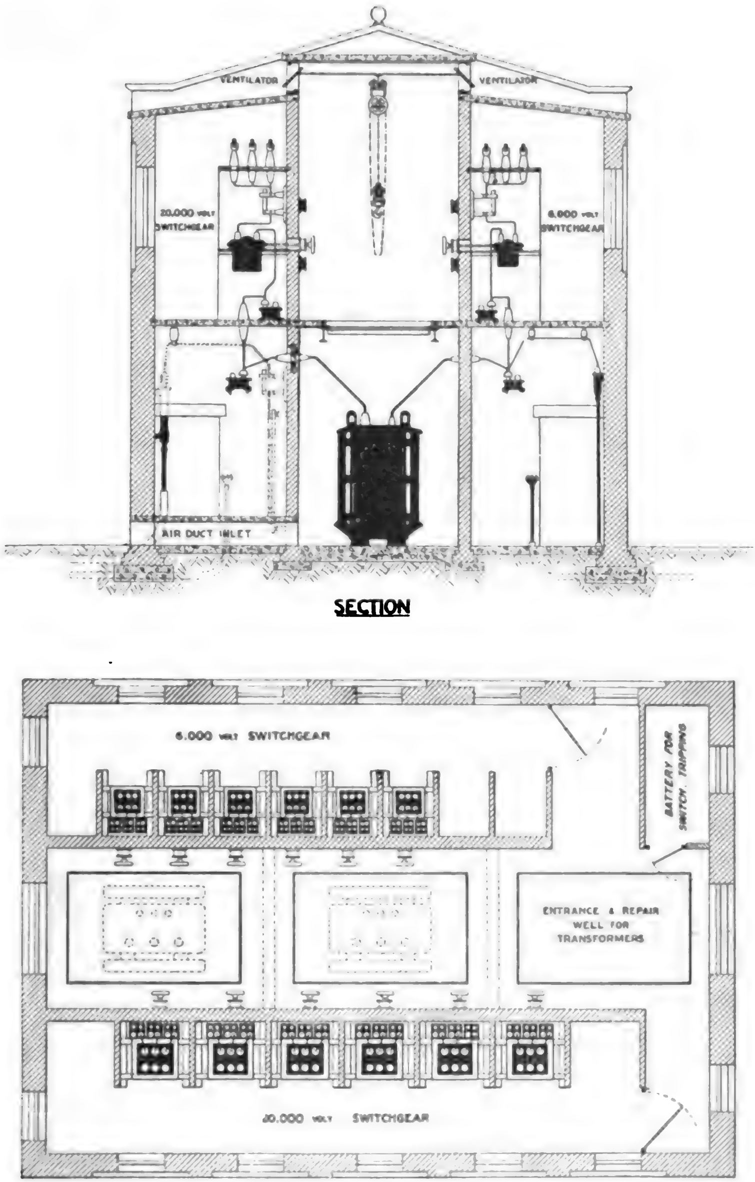
Fig. 11 shows a step-up sub-station accommodating 12,000 k.v.a., of transforming plant, divided into four sections of 3,000 k.v.a. each. The transformers are oil insulated and water cooled, the heat being extracted by means of a special cooler (through which the oil and



— PLAN —

FIG. 11

water are pumped) placed in the lean-to at the side of the building. Switchgear for one side only of the transformers is shown in the design, the other side being controlled by switchgear placed in an adjoining power station. It will be noticed that this sub-station differs from previous examples, in that provision has been made for lifting the



SECTION

FIRST FLOOR PLAN

FIG. 12.

transformer inside the building. In the case of 3,000 k.v.a., units weighing upwards of 25 tons, this is essential for minor repairs and for periodical examination of the transformer.

An interesting arrangement of sub-station which does not fall entirely within either of the two types arbitrarily assumed is indicated in Fig. 12. These sub-stations have been installed at the junction-

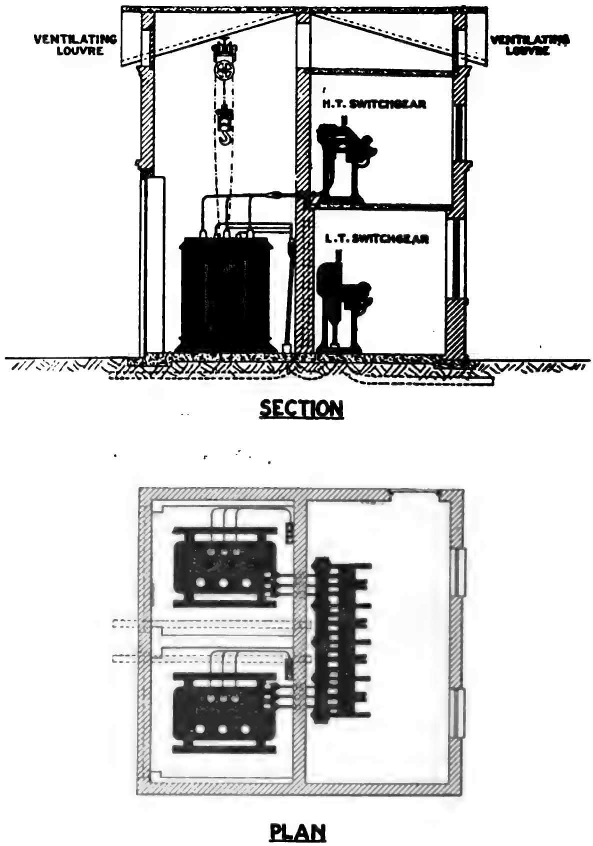


FIG. 13.

points of the trunk mains on a 20,000-volt system where the energy is transformed to 6,000 volts for general distribution. They have, therefore, extremely important duties, and it is impossible to estimate the ultimate maximum load. In these circumstances the sub-stations are designed with each section suitable for naturally cooled transformers up to sizes of 1,000 k.v.a., but may be arranged to accommodate artificially-cooled units up to 3,000 k.v.a. each. As an attendant is

necessary on account of switching operations, he can give the necessary attention to the transformer cooling plant. A crane is provided for lifting the transformers.

It is arguable that the same reasons which make lifting apparatus necessary for the artificially cooled transformers also apply to the naturally cooled apparatus. The question is somewhat involved, and is governed by the use likely to be made of the lifting apparatus. This is almost entirely a matter of individual experience depending on the amount of trouble met with. In any case repairs requiring more than one or two days should be carried out at a central repair shop, where proper apparatus is available for repairing, drying out and testing the transformers.

On the other hand, it is objectionable to have to transport a transformer some distance to the repair shop for the sake of inspection and adjustment only, although, of course, this is to be preferred to lifting it out of the case in the open air.

An arrangement of sub-station developed from Fig. 5, but including the lifting accommodation, is shown in Fig. 13. The conditions under which this design should be used in preference to that shown in Fig. 5 must remain a matter of individual opinion based upon personal experience.

In conclusion, the author does not claim any special merit in the designs here shown, except that they are a consistent interpretation of the principles assumed to be essential at the commencement of the paper, namely: Maintenance of sufficient reserve of plant, prevention of consequential damage, and facility of maintenance.

Opinions will, no doubt, differ respecting the relative importance of these principles, and the designs shown may be taken as representing the degree of importance attached to each by the author. The acknowledgments of the author are due to Mr. R. W. Gregory, who is largely responsible for the various designs shown in the Figs. and the preparation of the drawings illustrating this paper.

Discussion before the Newcastle Local Section.

Mr. J. A. Anderson: The author has dealt with the matter very fully, and has given typical examples of all the sub-stations in the Newcastle Companies' system. The earlier designs did not allow sufficient ventilation for the transformers. The latter type are very good examples of what static sub-stations should be like. The ventilating flues are absolutely necessary for the efficient ventilation. The only sub-station shown in the paper which has not yet been put into commission is that shown in Fig. 11, where artificial cooling has been adopted. The expense of the oil cooler is a considerable item, and I do not know whether it would not be better to go to a little further expense and instal larger transformers to take the load without artificial cooling. As it is the arrangement is complicated, and there is always a danger of the oil leaking or the water getting into the oil, due Mr. Anderson.

Mr. Anderson. to the tubes in the cooler pitting. In this respect a surface cooler might be used with advantage, made up of cast-iron pipes, with the cooling water running down the outside. Referring to the sub-station shown in Fig. 12, this sub-station is very badly ventilated, the transformers getting very hot.

Mr. Riseley. Mr. H. L. Riseley: I am not in a position to criticise the details of the paper, but I think it is most interesting and instructive, and might form the nucleus of a text-book entitled, "Evolution of the Sub-station." The chief thing the author has neglected in the design of these sub-stations is of primary importance—the location of the site and the accessibility of the transformers; for instance, Fig. 2, it is impossible to get the back transformer out without dismantling the transformer nearest the door. In another sub-station on the system it is quite impossible to get the transformers out without cutting a 20,000-volt cable, which comes right across the doorway. Moreover, it is a very difficult and lengthy performance to get the transformers into the sub-station, as in many cases there is no approach except across, perhaps, a field or unmade ground, and there are no appliances for lifting the transformers on to a lorry outside the building, and not even arrangements made to raise a pair of shear legs for this purpose. In justice to the author it is only right to say that some of the 20,000-volt sub-stations have cranes inside. The facility for handling transformers should not be overlooked, as in case of breakdown time is of great value, and when changing transformers, say at a week-end, the same applies. Another point I cannot understand is why flat roofs are always used—in fact, I think I am right in saying flat roofs are not used anywhere else in the North of England. This makes a very expensive construction, as it is essential for these roofs to be water-tight, and it is necessary in every case to asphalte them, which costs a lot of money. I would like to know why a gable roof cannot be used. I see no difficulty in the way of extension, and it would undoubtedly be cheaper. Mr. Anderson has already touched on the water-cooled oil-immersed transformer. I would like to point out in the particular instance he refers to that, should a tube leak in the cooler, all the oil will automatically syphon out of the transformer. Also, there are too many safety devices on this apparatus: recording thermometers, which ring a bell when the oil gets too hot, also a bell to ring should the level of the oil alter much, etc. All this is very nice, but all takes a certain amount of maintenance.

Mr. Turnbull. Mr. C. Turnbull: This paper clearly brings out the great expense which is involved in the distribution of current on a large system. Indeed, it is more and more being found that the cost of distribution is becoming one of the most important factors in a large supply system, and it promises eventually to become the chief factor. Even the load-factor is not more important, for obviously a private plant could supply 1,000,000 units per annum at a 10 per cent. load factor more cheaply than a central station could supply the same units over a scattered area even at a much better load factor. To enable this problem to be

clearly understood I introduced the term "density factor" some years ago. The density factor is obtained by dividing the total cost of distribution by the total units distributed, this giving the cost to be debited against each unit for distribution. Were they published regularly as load factors, it would be discovered that the density factors are a controlling element in the success or failure of many stations, being perhaps not less important than the older and better known term, load factor. Mr. Turnbull.

Mr. E. FAWSSETT: With regard to Mr. Turnbull's remarks on cost of distributing power, I might mention that on the Tyneside Power Company's system the transformer core loss alone amounts, owing to the large amount of reserve static plant, to no less than 10,000,000 units per annum. The author suggested that one of the disadvantages of the arrangement shown in Fig. 2 is the difficulty of metering the combined output; but this may very simply be got over by inserting current transformers to each supply and joining them up in parallel to the meter, this being quite an accurate and satisfactory method. The author infers in his paper that the ventilation is designed on most scientific lines—the basis of the losses of the largest transformer the chamber would hold; but my experience of many of the sub-stations is that the direction of the wind has an enormous effect on the temperature of the air surrounding the transformer, and I doubt if in any of the designs the draught is sufficiently strongly established; in fact, I look on the ventilation as the weak feature of an excellent series of designs. In Fig. 9 I see roller gaps shown for 20,000-volt operation. Seeing that this type has a big ratio between the sparking-over and quenching voltages, they must be set high above working pressure; whereas the factor of safety of a 20,000-volt system is not as high as that of a 6,000-volt one, and consequently these gaps cannot protect the apparatus from small surges. It seems to me imperative that horn breaks should be used, as these can be set with a very small margin, and can also take care of far more power than the roller type. I should be glad to know if there have been any recent experiments to prove what is the real action in a horn-gap breaking small currents up to, say, 10 amperes at high pressure. The old idea was that the heated air gave a non-conducting path, and some experiments I have made with the horns set horizontally certainly confirm this, though I see Mr. Andrews reported in the discussion on Mr. Peck's paper three years ago that he had made some experiments with heavier currents, in which the results pointed to a purely electromagnetic action. Any further information on this score would be extremely interesting. Mr. Fawssett.

Mr. C. VERNIER: I think the author's paper should prove extremely useful to those power company undertakings which have not yet reached the advanced stage of development that we have in this district, and also to those who have to erect a sub-station in isolated cases. Most people have not yet got beyond the design shown in Fig. 2, which one sees commonly illustrated in the Press, in connection with private supply to works, etc. I should like to ask the author about Mr. Vernier.

Mr. Vernier.

the curve, Fig. 1, whether this curve is independent of primary pressure; for instance, whether it would hold good for a transformer wound for 3,000 volts as well as one wound for 20,000 volts, the total capacity in kilovolt-amperes being the same in each case? It is interesting to note on page 464 that one can do almost anything to the design of the building without affecting the cost very much, and this, of course, lends itself to full exercise of ingenuity on such designs. Fig. 3, I may say, was about the first type of double-story sub-station designed for the power companies on the north-east coast; previous to that all designs had been Fig. 2. I do not quite agree with the remark that the author makes on page 467 regarding this sub-station, where he makes a strong point of the disadvantage of having to bring all the cables out at one end. I am well acquainted with this particular sub-station, the installation of which I supervised; and the reason for bringing the cables out in this manner was really due to the peculiarity of the site, but cannot be said to be a disadvantage of the design, as if you reverse the position of the high-tension and low-tension switchgear, it is quite possible to take out the low-tension cables directly behind the board. Of course, as the figure is shown, this cannot be done, since the cable pipes would obstruct the doors. I do not think the paper should be called "The Design of Static Sub-stations," but rather "The Design of Static Sub-station Buildings," for the design of a static sub-station, as I understand it, does not only include the arrangement of buildings and plant. I think the author might have given us something in connection with switchgear and transformers, etc. It would be interesting to hear, for instance, what the author thinks of the various methods of cooling transformers—air-cooled against oil-cooled, and, again, artificial as against natural cooling. Various methods of artificial cooling might have been dealt with—for instance, whether we should cool the oil by passing it through a worm immersed in circulating water, or whether we should immerse the cooling pipe in the transformer tank, through which water is circulated, and then, again, the advantages or otherwise of air-blast cooling. As regards switchgear, I think most of the types of switchgear are illustrated in the paper. Most recent designs of sub-stations, it will be noticed, are equipped with Reyrolle ironclad switchgear, but I think the comparison of various types of switchgear would have been useful.

Mr. Shearer.

Mr. A. G. Shearer: I should like to ask for the author's views on the total cost of sub-station equipment when single-phase transformers are installed, as compared with 3-phase transformers. Capital outlay for sub-stations equipped with the former arrangement, even if a spare single-phase transformer was installed, would, in my opinion, compare very favourably with a sub-station equipped with a duplicate 3-phase transformer, together with its high-tension and low-tension switchgear. One reason why mesh-connected single-phase transformers have not been more extensively used is owing to the difficulty in supplying alternating-current lighting, but this difficulty has been overcome by the auto-balancing transformers, which are very efficient.

Mr. F. O. HUNT: With regard to Mr. Fawssett's remarks upon the real action of horn-gap lightning arresters, it occurs to me that a similar point was largely dealt with in a paper read at Manchester by Professor Schwartz and Mr. James. It was there shown that the position of the cables leading current to the gap was very important. It is therefore probable that the difference between Mr. Fawssett's results and those quoted by him may arise from different arrangements of cable connections being used in the two sets of experiments. Mr. Hunt.

Mr. G. L. PORTER: Since seeing Mr. Fawssett's tests I have referred to the particulars given by Mr. Andrews of his work, and find that his tests were not really of horn arresters at all, but were made in connection with the use of horns to clear the arc consequent upon blowing fuses. All the tests described were carried out with heavy currents (blowing at least a No. 18 S.W.G. copper wire), when powerful electromagnetic effects would, of course, occur, whereas Mr. Fawssett's tests were made with a horn arrester with the usual series resistance limiting the current to 1 or 2 amperes, the voltage being raised above the breakdown voltage of the horn-gap to start the arc. Mr. Porter.

Mr. H. W. CLOTHIER: The author has shown in a very complete and interesting way how the design of sub-stations has been evolved, starting from the stage when we had to work out the best way to fit switchgear and transformers into some existing room, perhaps a railway arch or a disused cellar, to the time when the sub-stations consist of a well-thought-out, properly ventilated building of standard construction which is shaped to house standard designs of switchgear, transformers, and methods of connecting. One of the speakers has raised the question as to what an up-to-date sub-station will be like in ten years' time. In making a forecast from the information in the paper the following appear to me to be the leading factors to take into consideration:— Mr. Clothier.

1. Development in the detail construction of the apparatus used.
2. The matter of ventilation.
3. The tendency of the present time towards the complete enclosure of all conductors from the generators to the load within a continuous metallic armouring.

From the progressive examples of switchgear shown in the paper one might naturally expect in ten years' time to have switchgear so strong and perfect that it would work quite well in the open. As to the second point, it seems to me that the trouble and expense involved at the present time in obtaining good ventilation is brought about by the fact that the transformers are enclosed within a building. In this case the problem of ventilation would be best solved if the building could be dispensed with. The third point is prominent in the modern designs shown in the paper; but I think there is possibly room for improvement in respect to the leads which join between the switchgear and the transformers, particularly when these leads are single unarmoured cables. For instance, would it not be better to have the

Mr. Clothier. static transformers plugged into ironclad contacts forming a continuation of the switchgear? Assuming that the above points continue to be the controlling features, it seems to me that the sub-station of the future will consist of apparatus so completely and effectually enclosed that it can be placed in a field without any roof or building to cover it.

Mr. Wood. Mr. W. W. Wood: Horn arresters appear to be in favour for overhead lines, and spark-gaps for underground cables. At Harton Colliery horn arresters are used exclusively, and these seem to favour Saturday afternoons for sparking over.

Mr. Viall. Mr. H. R. Viall: The author has not mentioned the outside type of sub-station, which is the cheapest on the Newcastle Company's system, and is situated at Ponteland. It consists of a 6,000/440-volt transformer in a weatherproof case erected on four poles at the terminus of a 6,000-volt overhead line. Messrs. Merz and McLellan might have developed further on these lines. I think the dwelling-house type of sub-station would have been a great adornment to the author's paper, and he should have had an illustration of the Aykley Heads substation at Durham, with its elaborate frontage, included in the paper.

Mr. Butcher. Mr. J. Butcher: I always failed to see any bad results due to the arresters at Harton Colliery, and asked Mr. Wood if he could give any particulars of them. I have carefully examined them both when they were dead and when they were alive, but they always appeared to be satisfactory.

Mr. Hunter. Mr. P. V. Hunter (*in reply*): One thing I am pleased to see is that no one seems to have taken any serious objection to the principles on which the designs are based, although a number of points have been raised about the apparatus. Respecting the criticism of the water-cooled transformers on Fig. 11, the alternatives are naturally cooled transformers *versus* artificially cooled ones. There is, of course, a great deal of difference in the cost of these alternatives so far as transformers and buildings are concerned. Naturally cooled apparatus would cost something like double the water-cooled. I must say, apart from cost, I would much prefer to see naturally cooled transforming apparatus everywhere. I do not think there is any probability of the oil leaking into the water or even leaking away. The coolers were first designed as condensers by a local firm for the Admiralty under a rigid guarantee against leakage between the fresh-water and salt-water systems. As a further precaution, an extra heavy tube-plate has been used with the tubes expanded into it. In order to take up any contraction and expansion of the tubes they have been given a bend. Mr. Riseley mentions that all the oil might leak out of the transformer before any one knew about it, but the arrangement is such that a bell will ring under those conditions, due to the temperature rising. Regarding ventilation Mr. Anderson refers to Fig. 12, which is certainly not as well ventilated as some sub-stations which were designed afterwards. It should be borne in mind that the sub-station is intended not only for the naturally cooled transformers but also for artificially

Mr. Hunter.

cooled, and with the artificially cooled no ventilation is required. It is difficult to arrange more efficient ventilation than that shown, and the design must be looked upon as a compromise. Mr. Riseley referred to the necessity of facilities for handling heavy transformers when installing or removing them. This is, perhaps, hardly a matter affecting design. If the difficulty is serious, I would suggest the construction of a special portable apparatus, for which proper provision can be made in the sub-station building, to enable the transformers to be lifted straight off the waggon and deposited in position on the sub-station floor. The difficulty is to know where to stop in sub-station buildings, and the cost of a special crane such as Mr. Riseley suggests for each sub-station would be a serious item. Mr. Riseley has also referred to the flat roof—there is difficulty in extending with anything but a flat roof. Take, for instance, Fig. 7. The joists supporting the roof are longitudinal with flat roofs as in Fig. 4; the joists go straight across, and it is obvious that Fig. 4 is much more readily extended than Fig. 7. With certain designs of switchgear, I think a concrete roof is unnecessary; although concrete is liable to crack with a flat roof and not so liable with a pent house roof, I fear that no one would care to take the risk of leaving a pent house roof without an asphalte covering. As regards the question of cost of distributing, Mr. Turnbull does not suggest anything which would cut down the cost of the designs given in this paper without sacrificing some of the safeguards which are considered necessary. In general the result of trying to cut down cost is that the designs become more complicated. Mr. Fawssett refers to the question of metering on Fig. 2, and his suggestion is quite a feasible one and might well be adopted. As a matter of fact, I think it would be a little more expensive than the double busbars, as both bars are carried on the same brackets with a piece of micanite insulation between the two sets. Mr. Fawssett also wishes to know why roller spark-gaps are used on the 20,000-volt gear. I agree they are very little use for dealing with a real voltage surge. The contractors maintaining the 20,000-volt cables consider them essential, and as more effective apparatus would be also more expensive the roller gaps are used. The system has run quite satisfactorily with them. In reply to Mr. Fawssett, Mr. Wood, and Mr. Hunt respecting the operation of horn-gaps, Mr. Porter made some interesting remarks. I think in view of Mr. Fawssett's uncertainty, he should get to the bottom of the matter by making some further tests. The old type of sub-station in Fig. 3 does not show the ventilating arrangements which have since been added, as I thought the development of the problem would be understood better if they were omitted. I have never heard it mentioned before, but I have no doubt it is the case that the direction of the wind has an effect on the cooling of some early sub-stations. With the ventilating flues I think the cooling is more or less independent of the wind. I do not see how wind would stop ventilation, but I can see how the wind would help.

Mr. Hunter. The question of the cost curve has been raised by Mr. Vernier. This does not hold for different pressures, but does not differ greatly. With higher pressures the whole curve is raised slightly, and the cost per kilovolt-ampere is a little greater for all sizes. In trying to get a concise title I may perhaps have sacrificed something in the description. Mr. Shearer raises the question of single-phase transformers, his point being, I take it, to cut down cost. In the event of a breakdown, however, until the other transformer was got into commission, which would probably take some hours, the supply to the consumer would be interrupted, to his great annoyance and expense. Mr. Clothier's suggestion of the ironclad sub-station which is not a sub-station, is very interesting. In reply to his objection to the insulated leads, I would point out that all connections except those below 600 volts are metal covered. For the higher pressures, with ironclad switchgear, lead-covered cables are used, sometimes single cables, and sometimes 3-core, as may be most convenient. He has therefore really got his metallic sub-station equipment except that he has a building as well. The transformer manufacturers are, however, not so enterprising as Mr. Clothier, and they would object strongly to putting their transformers out in the open. Mr. Wood deals with the question of horn arresters as against electrolytic arresters. There is no doubt that the electrolytic arresters are much more effective. Mr. Viall has referred to Ponteland sub-station. I am very sorry I have not a slide of it. It consists of a special watertight transformer erected on poles at the termination of a high-tension pole-line and is quite unsuitable for important supplies on account of the risk of interruption to supply.

A GRAPHICAL TREATMENT OF THE SKIN EFFECT.

By Professor ALFRED HAY, D.Sc., Member.

(*Paper received December* 5, 1910.)

The fact that an alternating current is not uniformly distributed over the cross-section of a conductor has for a long time been well known to all electrical engineers, and the changes in the resistance and self-inductance of a cylindrical conductor arising from this cause have formed the subject of several analytical investigations. The contributions of Clerk Maxwell, Oliver Heaviside, Lord Rayleigh, and Lord Kelvin to the solution of this problem are well known to those interested in the subject, and the formulæ and tabulated numerical results given by these investigators have been frequently referred to by writers on alternating currents. The most recent and thorough analytical treatment of this problem we owe to Dr. Alexander Russell.* An elementary explanation of the general nature of the skin effect has also been given; but no attempt seems hitherto to have been made to deal with the subject in a quantitative manner by a purely elementary method. It is the object of this paper to develop such a method. As will be seen, the method has the great advantage of presenting to the mind in a very vivid manner the purely physical aspect of the problem.

In what follows, we shall confine our attention to cylindrical conductors so arranged that everything is symmetrical about the axis of the conductor, the lines of magnetic induction being represented by circles having their centres on the axis of the conductor. Imagine a long, straight cylindrical conductor surrounded by a coaxial infinitely thin shell of negligible resistance lying infinitely close to the surface of the conductor but insulated from it, and let an alternating current be sent through the conductor, the surrounding shell forming the return path for the current. We may term the quotient of the potential difference by the current in such a circuit the "internal impedance" of the conductor. This may be regarded as made up of the "effective

* *Proceedings of the Physical Society of London*, vol. xxi., p. 581, 1907–1909.

resistance" of the conductor (= power dissipated in conductor divided by square of current) and its "effective reactance," these three quantities forming the well-known impedance triangle. Since the reactance of the conductor in the case under consideration arises wholly from magnetic lines within its substance, we may conveniently term the effective reactance in this case the "internal reactance" of the conductor.

Suppose next that the surrounding shell forming the return path for the current is made to expand, so that there is a considerable space formed between the outer surface of the cylindrical conductor and the shell. This space becomes filled with magnetic lines and increases the reactance. That portion of the reactance which arises from such lines may be conveniently termed the "external reactance." Since everything remains symmetrical about the axis, it is evident that the only effect of the external reactance is to add to the reactance component of the impressed potential difference, the current distribution within the conductor not being in any way affected. A similar result will hold good if for the coaxial shell we substitute any other form of return conductor, provided always that this return conductor is sufficiently far from the cylindrical conductor to prevent any appreciable disturbance of the symmetry of the internal magnetic field of the conductor. We are thus led to the following result, on which the method about to be explained is based :—

> *So long as the symmetry of the internal magnetic field of a cylindrical conductor remains unaffected, changes in the magnetic flux external to the conductor have no effect on the current distribution.*

Hence if we suppose our cylindrical conductor divided into a central cylindrical core and a number of coaxial shells surrounding it, the removal of any number of shells from the outside of the conductor will not in any way affect the law of current distribution in the remaining or internal shells, since so far as these shells are concerned, the flux contributed by the shells which have been removed is an external flux. Similarly, the addition of any shells to the outside of the conductor so as to increase its diameter will leave the law of current distribution in the originally existing shells unaltered.

Making use of this principle, we first approximately determine the current distribution in the central core, and then in the successive shells which we imagine to be built up around the core, until the desired diameter of conductor is reached. We begin by assuming a certain current density at the centre of the conductor, and suppose that the current density in each successive shell increases at a uniform rate from its inner to its outer surface.

In determining the current densities in the consecutive shells we

shall suppose the current density to be split up into two components, which are in quadrature with each other, one of these—the x-component—being in phase with the current density at the centre, and the other—the y-component—in quadrature with it.

The details of the method will be best understood by considering a numerical example.

Let the conductor be 1,000 metres long, and have a resistivity at the working temperature of $1{\cdot}8 \times 10^{-6}$ ohm/cm. cube. We shall assume the standard frequency of 50, and shall suppose the conductor to be built up by gradually adding coaxial shells around a central core of 1 mm. radius, the radial depth of each shell being also 1 mm.

Let us assume a current density of 10 amperes/sq. cm. at the centre of the core. This gives for the resistance drop per centimetre length $1{\cdot}8 \times 10^{-6} \times 10 = 1{\cdot}8 \times 10^{-5}$ volt, and for the total drop along the 1,000 metres 1·8 volt. We provisionally assume that the current density over the central core of 1 mm. radius is uniform, so that the total current is $\pi \times 0{\cdot}1^2 \times 10 = 0{\cdot}3142$. The value of H at the surface of the core is thus $2 \times 0{\cdot}03142/0{\cdot}1 = 0{\cdot}6283$, and since H increases at a uniform rate from the centre—where its value is zero—to the surface, the mean value of H is 0·3142, and the flux linked with an infinitely thin filament coincident with the axis of the core is $0{\cdot}3142 \times 10^4$ lines. The reactance potential difference corresponding to this flux is given by $p \times$ flux, where $p = 2\pi \times$ frequency $= 314{\cdot}2$. Thus the reactance potential difference for the axial filament is—

$$314{\cdot}2 \times 0{\cdot}3142 \times 10^4 \times 10^{-8} = 0{\cdot}00988 \text{ volt},$$

and this potential difference is in quadrature with the current density at the axis. Now, at the surface of the core, where there is no internal reactance, the reactance component of the potential difference will give rise to a current density in quadrature with that at the axis. This current density is obtained by dividing the potential gradient of the reactance potential difference by the resistivity. Thus y-component of current density at surface of core—

$$= 0{\cdot}00988 \times 10^{-5}/1{\cdot}8 \times 10^{-6} = 0{\cdot}0549.$$

The x-component being 10, we see that the resultant current density at the surface is practically identical with that at the axis, but that it is in advance of it as regards phase by the angle $\tan^{-1}\dfrac{0{\cdot}0549}{10} = 0^\circ\ 19'$. Assuming the y-component of the current density to increase at a uniform rate from a zero value at the axis to the value 0·0549 at the surface of the core, we find for the total y-component of the current in the core the value 0·00115 ampere. This gives for the y-component of H at the surface $\dfrac{2 \times 0{\cdot}000115}{0{\cdot}1} = 0{\cdot}0023$.

The above results may be tabulated as follows :—

x-component of current density at axis $= d_x' = 10$ amperes/sq. cm.
y-component of current density at axis $= d_y' = 0$.
x-component of current density at surface $= d_x = 10$.
y-component of current density at surface $= d_y = 0{\cdot}0549$.
x-component of magnetic force at surface $= H_x = 0{\cdot}6283$.
y-component of magnetic force at surface $= H_y = 0{\cdot}0023$.
Total x-component of current in core $= i_x = 0{\cdot}3142$.
Total y-component of current in core $= i_y = 0{\cdot}00115$.
Phase displacement of surface current density $= \theta = 0^\circ\ 19'$.

We next place around our core a coaxial shell of 1 mm. radial thickness, and proceed to determine the current densities d_x and d_y at its outer surface, the current densities at the inner surface being identical with those at the outer surface of the core. Since the current in the shell will give rise to additional magnetic lines, it is evident that if the current in the core is to remain unaltered a higher impressed potential difference must now be provided, owing to the increased reactance of the axial filament. The current distribution in the shell may be determined as follows.

We provisionally assume that the rate of change of d_x remains unaltered—*i.e.*, equal to zero, so that we still have $d_x = 10$ at the outer surface of the shell. The total x-component of the current is now $i_x = 1{\cdot}257$.* Hence at the outer surface of the shell we have—

$$H_x = 2 \times 0{\cdot}1257/0{\cdot}2 = 1{\cdot}257.$$

Since H_x as before increases uniformly from zero on the axis to $1{\cdot}257$ at the outer surface of the shell, its mean value is $0{\cdot}6285$, and the x-component F_x of the total flux linked with the axial filament is $0{\cdot}6285 \times 0{\cdot}2 \times 10^5 = 1{\cdot}257 \times 10^4$. The reactance potential difference V_y is therefore $314{\cdot}2 \times 1{\cdot}257 \times 10^4 \times 10^{-8} = 0{\cdot}0395$. This gives rise to a current density $d_y = \dfrac{0{\cdot}0395 \times 10^{-5}}{1{\cdot}8 \times 10^{-6}} = 0{\cdot}219$ at the outer surface of the shell.

We thus have $d_y = 0{\cdot}0549$ at the inner, and $0{\cdot}219$ at the outer surface of the shell. From this we find for the y-component of the current in the shell the value $0{\cdot}01376$.* Adding this to the y-component previously found for the core—viz., $0{\cdot}00115$, we get for the total y-component the value $0{\cdot}01491$. Hence $H_y = 2 \times 0{\cdot}001491/0{\cdot}2 = 0{\cdot}01491$ at

* If the current density have the values d_1 and d_2 at the inner and outer surfaces respectively of a shell whose inner and outer radii are r_1 and r_2 respectively, and if the density increases at a uniform rate from the inner to the outer surface, then it may be shown (by a simple integration) that the total current in the shell is—

$$\text{area of shell} \times \frac{2(d_2 r_2 + d_1 r_1) + d_1 r_2 + d_2 r_1}{3(r_2 + r_1)}.$$

As an alternative method, the current may be determined by a process of graphical integration.

the outer surface of the shell. If, now, we plot the values $H_y = 0{\cdot}0023$ and $H_y = 0{\cdot}01491$ as ordinates against the values $0{\cdot}1$ and $0{\cdot}2$ (distances from axis) as abscissæ, and draw a curve through the origin and the two points so determined, we find for the area of the curve the value 8×10^{-4}. This represents the y-component of the flux per centimetre length of our conductor, so that the total y-component of the flux linked with the axial filament is 80. The corresponding induced E.M.F. is—

$$314 \times 80 \times 10^{-8} = 0{\cdot}000251,$$

which is negligible in comparison with the resistance drop (1·8) along the axial filament. It is to be noted that this E.M.F. is co-phasal with the axial current density, so that its effect (if appreciable) would be to reduce the x-component of the impressed potential difference, and hence to reduce d_x at the outer surface of the shell.

The phase displacement of the current density at the outer surface of the shell relatively to the axial current density is—

$$\tan^{-1} \frac{0{\cdot}219}{10} = 1^\circ\ 15'.$$

We now place another shell of 1 mm. radial thickness around our conductor, thereby increasing its radius to 3 mm. We again provisionally assume d_x to remain unaltered, and, proceeding as before, we find the following values :—

i_x (total x-component of current in conductor) $= 2{\cdot}827$.
$H_x = 1{\cdot}885$ at surface.
F_x (total x-component of flux) $= 2{\cdot}827 \times 10^4$.
V_y (reactance potential difference) $= 0{\cdot}0888$.
$d_y = 0{\cdot}4935$ at surface.
y-component of current in shell $= 0{\cdot}0574$.
i_y (total y-component of current in conductor) $= 0{\cdot}0723$.
$H_y = 0{\cdot}0482$ at surface.

On plotting the value $H_y = 0{\cdot}0482$ in the diagram connecting H_y with distance from axis, finding the area of the curve as before, and multiplying by 10^5 (length of conductor), we find for the total y-component F_y of the flux linked with the axial filament the value $F_y = 366$. The corresponding induced E.M.F. is $E_x = 0{\cdot}00115$. Since, as already mentioned, this E.M.F. is in phase with the axial current density, the component V_x of the impressed potential difference in phase with the axial current density is $V_x = 1{\cdot}8 - 0{\cdot}00115 = 1{\cdot}7988$. Hence the assumed value $d_x = 10$ at the surface of the conductor requires a small correction, the true value being $10 \times \frac{1{\cdot}7988}{1{\cdot}8} = 9{\cdot}993$.

The phase displacement of the surface current density relatively to that along the axis is $\tan^{-1} \frac{0{\cdot}4935}{9{\cdot}993} = 2^\circ\ 50'$.

We next place an additional shell of 1 mm. radial thickness around the conductor, thus making its radius equal to 4 mm. We provisionally assume that the rate of change of d_x with distance from axis changes by the same amount as before—*i.e.*, by 0·007 per millimetre. The new rate of change will thus be 0·014 per millimetre, giving for the value of d_x at the new surface $9{\cdot}993 - 0{\cdot}014 = 9{\cdot}979$. The work is then continued as before, the values of the various other quantities being determined, and a correction being applied if necessary to the provisionally assumed value of d_x at the surface.

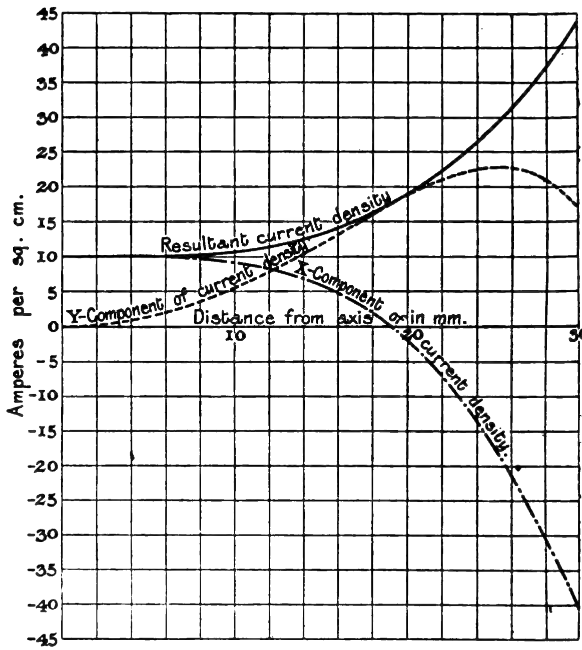


FIG. 1.—Variation of Current Density with Distance from Axis.

By proceeding in this manner we can build up our conductor to any desired thickness. Table I. contains the results of the calculation up to a radius of 3 cm.

Some of these results are exhibited graphically in Figs. 1 and 2. Referring to Fig. 1, we see that the x-component of the current density steadily decreases, passes through a zero value, and then increases in the negative direction. The y-component starts from a zero value, increases very slowly at first, then more rapidly, passes through a maximum value and decreases. Had we extended Table I. to larger distances from the axis, we should have found that each component of the current density is represented by a wave which passes through

Shell.	d_x.	i_x.	H_x.	F_x.
Millimetres.				
0–1	10·00	0·314	0·628	3,140
1–2	10·00	1·260	1·260	12,570
2–3	9·99	2·830	1·885	28,270
3–4	9·98	5·020	2·510	50,240
4–5	9·95	7·840	3·140	78,470
5–6	9·90	11·270	3·760	112,940
6–7	9·82	15·290	4·370	153,570
7–8	9·69	19·880	4·970	200,270
8–9	9·47	25·000	5·560	252,900
9–10	9·21	30·550	6·110	311,230
10–11	8·81	36·500	6·640	375,000
11–12	8·35	42·700	7·114	443,800
12–13	7·77	49·000	7·550	517,100
13–14	6·96	55·300	7·900	594,300
14–15	6·06	61·200	8·160	674,600
15–16	4·97	66·600	8·330	757,100
16–17	3·61	71·100	8·360	840,500
17–18	2·06	74·200	8·240	923,500
18–19	0·25	75·500	7·950	1,004,500
19–20	− 1·83	74·550	7·450	1,079,000
20–21	− 4·22	70·650	6·730	1,149,900
21–22	− 6·93	63·120	5·740	1,212,300
22–23	− 9·97	51·200	4·450	1,263,200
23–24	− 13·34	34·000	2·830	1,299,600
24–25	− 17·08	10·600	0·850	1,318,000
25–26	− 21·15	− 20·040	− 1·543	1,314,500
26–27	− 25·57	− 58·900	− 4·370	1,270,900
27–28	− 30·30	− 107·200	− 7·660	1,210,800
28–29	− 35·30	− 166·000	− 11·450	1,115,200
29–30	− 40·56	− 236·400	− 15·740	979,400

a succession of maxima, zero, and minima values. The total or resultant current density steadily increases, and so does its phase angle of advance relatively to the current density at the axis. The connection between the value of the current density and its phase angle of advance is clearly exhibited in the polar diagram of Fig. 2, in which the radius vector represents the current density, and the vectorial angle the phase angle of advance of the current density relatively to that at the axis. The numbers along the polar curve (which is the locus of the current-density vector) represent distances from the axis.

Knowing the current-density distribution, we can easily determine from it the total power dissipated in a conductor of given radius. For this purpose we first plot a curve, as in Fig. 3, whose abscissa represents the area of a conductor of given radius, while its ordinate gives us the

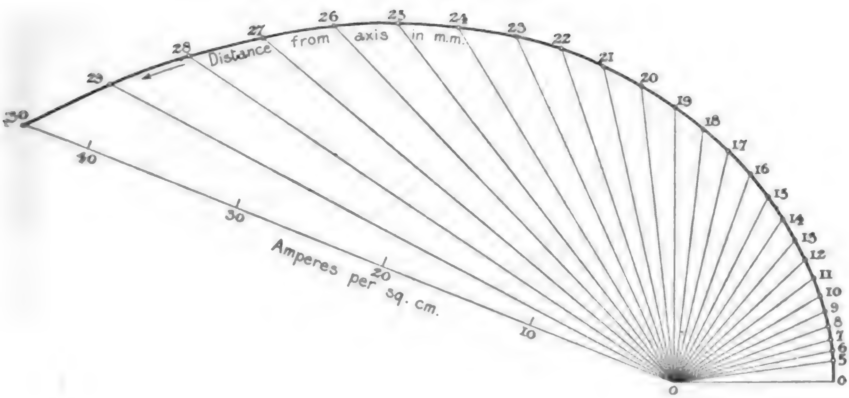


FIG. 2.—Polar Diagram of Current Density and Phase Angle.

rate of dissipation of energy per square centimetre of conductor cross-section at the surface of the conductor. In order to obtain points along this curve, we take the consecutive radii given in Table I., and find the areas of the corresponding circles; this gives us a number of abscissæ for our curve.

To find the corresponding ordinates we multiply the square of the current density d in Table I. by 0·18 ($= 1{\cdot}8 \times 10^{-6} \times 10^5$, the product of the resistivity into the length of the conductor). We next proceed to find the area of the curve so obtained, this area representing, for any given value of the abscissa, the total watts dissipated in a conductor whose cross-section is given by the abscissa. On dividing the total watts dissipated by the square of the total current in the conductor ($= i_x^2 + i_y^2$), we find its resistance to alternating currents of frequency 50, and the quotient of this resistance by the resistance to continuous currents (calculated in the ordinary way from the resistivity, length and

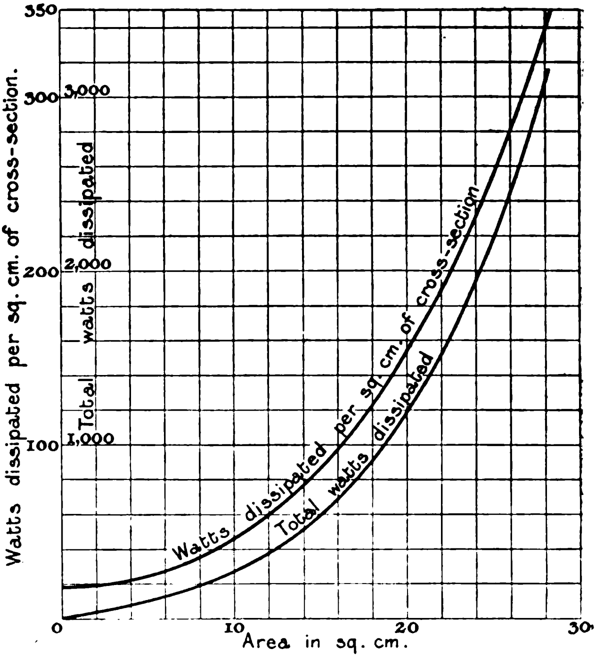


FIG. 3.—Determination of Power Lost in Conductor.

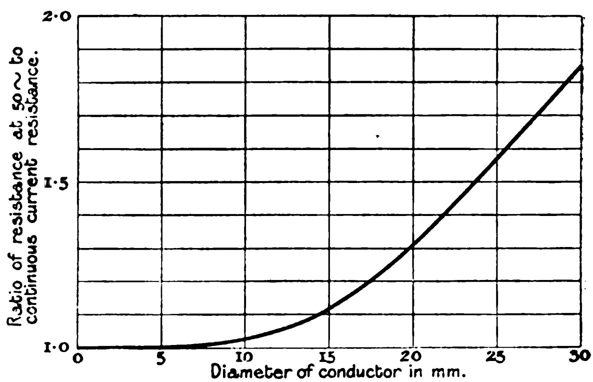


FIG. 4.—Ratio of Resistances corresponding to various Diameters of Conductor.

cross-section of the conductor) gives us the ratio of the two resistances. This ratio is plotted against the diameter of the conductor in Fig. 4. It remains at a value not far removed from unity until the diameter of the conductor exceeds 5 mm., then begins to increase, very slowly at first, then more rapidly, and after a diameter of 20 mm. has been reached, it nearly follows a straight-line law.

While the effective resistance of a conductor is *increased* by the crowding of the current towards the surface, the effective internal self-inductance is *decreased* by the same effect. It is easy to understand this result from general considerations. For if we imagine a cylindrical current sheet to start from near the axis of the conductor and to expand outwards like a ripple on water, it is obvious that as the sheet expands it becomes linked with less and less flux. From the data at our disposal

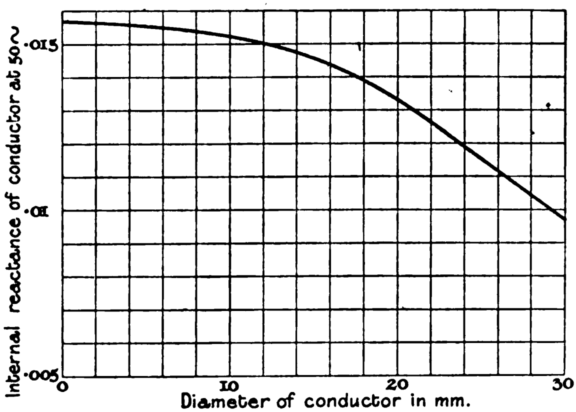


FIG. 5.—Relation connecting Internal Resistance with Diameter of Conductor.

we can easily calculate the values of the internal reactance corresponding to various diameters of conductors. For, using Table I., we have for the square of the internal impedance the expression $(V_x^2 + V_y^2)/(i_x^2 + i_y^2)$. On subtracting from this the square of the resistance to currents of frequency 50, we obtain the square of the reactance, and so the reactance itself. It is to be noted that for the smaller sizes of conductors this method does not yield accurate results, owing to the smallness of the reactance as compared with the resistance. But for the smaller sizes the internal self-inductance at 50 cycles per second will be nearly the same as that corresponding to a uniform current distribution, and this latter self-inductance is known to be (in C.G.S. units) $\frac{1}{2}$ per centimetre length of conductor, and to be independent of the size of the conductor. Hence the internal reactance, in ohms, of a cylindrical copper conductor of small diameter 1,000 metres long is $2\pi \times 50 \times \frac{1}{2} \times 10^{-4} = 0{\cdot}01571$ at a fre-

quency of 50. The difficulty of finding the value of the internal reactance for small diameters is thus overcome, and we are in a position to plot the curve of Fig. 5, which shows the gradual drop in the internal reactance with increasing diameter of conductor.

It is hardly necessary to point out that the method described is applicable to the case of a long, hollow, cylindrical conductor or tube, provided its internal field is represented by circles concentric with the tube. It may also be applied to solid or hollow cylindrical conductors of iron, and the effect of varying permeability is easily taken into account (we suppose the permeability to be uniform for any one shell, but to vary from shell to shell). Although the method may appear to be somewhat laborious, it has the merit of bringing within the reach of any engineer possessing a sound knowledge of the elements of alternate-current theory a problem of great complexity, whose solution could hitherto only be dealt with by the aid of very advanced mathematics.

ANNUAL DINNER, 1911.

The Annual Dinner of the Institution was held in the Grand Hall of the Hotel Cecil on Thursday, February 2, 1911. The President, Mr. S. Z. de Ferranti, presided at a gathering numbering about 360 persons. Among the gentlemen present were: The Right Hon. Lord Justice Fletcher Moulton, P.C., F.R.S., Mr. R. Kaye Gray, Past-President, Sir T. Barlow, Bart, K.C.V.O., President Royal College of Physicians, Mr. A. Siemens, Past-President, President The Institution of Civil Engineers, Sir James Crichton-Browne, F.R.S., Treasurer Royal Institution, Sir H. H. Cunynghame, K.C.B., Assistant Under Secretary Home Office, Professor J. Perry, F.R.S., Past-President, Sir Philip Magnus, M.P., Secretary Department of Technology, City and Guilds Institute, Professor S. P. Thompson, F.R.S., Past-President, Mr. L. Stokes, President Royal Institute of British Architects, Mr. J. Swinburne, F.R.S., Past-President, Dr. Gisbert Kapp, Past-President, Major-General Sir A. E. Turner, K.C.B., R.A., Mr. F. G. Ogilvie, C.B., Technological Department, Board of Education, The Hon. Sir W. Hall-Jones, K.C.M.G., High Commissioner for New Zealand, Mr. W. Duddell, F.R.S., Vice-President, Mr. W. H. Patchell, Vice-President, Mr. W. Whitaker Thompson, Chairman London County Council, Sir Somerset R. French, K.C.M.G., Late Agent-General for Cape of Good Hope, Mr. R. Hammond, Honorary Treasurer, Mr. J. F. C. Snell, Member of Council, Major W. A. J. O'Meara, C.M.G., Member of Council, Mr. Sam Mavor, Chairman Glasgow Local Section, Professor Sir W. A. Tilden, F.R.S., Mr. H. T. Butlin, President Royal College of Surgeons, Professor T. Mather, F.R.S., Member of Council, Mr. C. H. Wordingham, Member of Council, Lieut.-Colonel H. A. Yorke, C.B., R.E., Chief Inspector of Railways, Board of Trade, The Rev. Professor T. G. Bonney, F.R.S., President British Association, Mr. S. L. Pearce, Member of Council, Mr. H. Faraday Proctor, Member of Council, Mr. H. F. Donaldson, C.B., Superintendent Woolwich Arsenal, Mr. A. B. Kempe, F.R.S., Treasurer Royal Society, Mr. E. Moon, K.C., Mr. T. Harding Churton, Chairman Yorkshire Local Section, Professor W. C. Unwin, F.R.S., Vice-President Institution of Civil Engineers, Dr. W. N. Shaw, F.R.S., Director Meteorological Office, Mr. M. J. Railing, Chairman Birmingham Local Section, Mr. W. F. Reid, President Society of Chemical Industry, Mr. H. Percy Adams, Professor J. J. Dobbie, F.R.S., Principal of Government Laboratories, Mr. J. C. L. Coward, K.C., Mr. W. W. Cook, Member of Council, Mr. J. Christie, President Incorporated Muncipal Electrical Association, Mr. P. V. McMahon, Member of Council, Mr. A. H. Walton, Member of Council,

Mr. W. M. Morrison, Member of Council, Mr. E. Russell Clarke, Associate Member of Council, Mr. S. Morse, Associate Member of Council, Mr. J. E. Taylor, Associate Member of Council.

The PRESIDENT gave the toasts of "His Majesty the King," and of "Her Majesty the Queen, Queen Alexandra, His Royal Highness the Prince of Wales, and the other members of the Royal Family."

The RIGHT HON. LORD JUSTICE FLETCHER MOULTON, P.C., F.R.S., in proposing the toast of the Institution, said: I find myself in the enviable position of a guest, and I reflect that I am not only a member of this Society, but that I am an old member of the Council of this Society. My memory goes back, I may say, over the whole of the great years of this Society. If I had to describe the period in which I have lived, I should say that it was the age of electricity. When I took my degree at Cambridge, I read in the last few weeks with feverish haste a book that had just come out called "Maxwell's Treatise on Electricity," the book which wrote the mathematics and proclaimed the ideas which we now see crowned in wireless telegraphy. And when I came to London, having a passion for science, I joined the Society which seemed to me to most nearly devote itself to that subject, the society that was called the Society of Telegraph Engineers. They were very proud of themselves, and quite rightly so. They had, as the triumphs of the men who were prominent among them, such things as Wheatstone's wonderful telegraphic instrument and Professor Hughes printing telegraph; and that was, I may say, the idea of the world on the subject of the scope of electricity. And what have I seen in my time? The first indication of the dawn of the great work of electricity in the world was the discovery of the telephone—that electricity which we knew could convey signals at a distance along telegraphic wires was capable of transmitting the most marvellously minute forces, so minute that no one has ever been able, numerically, to measure them; and to reproduce at any distance acoustic vibrations accurately enough to make you recognise the voice of a living person. Well, that was the wonder of the world for a time. Who would have thought that electricity could have done this? Just at that time certain patents were almost running out which had been scarcely heeded by the world, the patents for the dynamo. Those who thought began to say—electricity is not only a delicate thing that can send signals. It can be used for power if needed. But still the feeling that something great was coming out of this new machine that supplanted the old electric battery, and that gave us current which we might make great by making our machines on a large scale, certainly called the attention of the world about 1880, to the question. Then there came what to my mind is the great event in the development of the practical work of electricity, the Exhibition of 1881 at Paris. I remember going there, and now as I look back I can see that the germs of everything but one of that which electricity has since done were to be seen there. We saw the electric light—the heated filament, heated to a temperature which made it brilliant. We saw the arc lamp. It was still in its

babyhood, and it blinked and winked. I remember that outside the Exhibition there was a car that ran up and down with a trolley, just as we see now in hundreds of thousands of miles all over the civilised world, just to show that electricity was equal to the task of traction. In one corner I remember there was an electric lift, and in another there was a circular saw that was driven by electricity ; so that at that time all the ideas of transmission of force by electricity were present, though in their babyhood. Information is telegraphed from every part to the great central towns ; orders are telegraphed from the great central towns to every part of the country. But 1881 marked the time when electricity stepped forward from being merely the nerves of the social world—it became its muscles. We realised that power was now the domain of electricity, and that power could be transmitted, just as of old knowledge could be transmitted. From that time I have seen gradual growth in scale of these services. I remember the early struggles for leave to put down electric light installations. I remember the greed with which the municipalities tried to rob the pioneers of all chance for a good return for their enterprise. I saw this country kept back for six years, the most important six years in the industrial development of a country that have occurred in my life—kept back while Germany and America got ahead of us, simply because there was that terror lest those who came first into the field might reap a remunerative harvest. But still electricity has borne all those set-backs. We have seen, as we saw at that time, electricity using its power of developing heat at any point of the circuit. We saw it then giving the electric light. What do we see now ? We see not only electric furnaces, but we see the power of electricity brought down to such a commercial use that we are having steel refined by it, and according to the papers I read, even economically refined by it—on such a vast scale can it be used. The traction that we saw, or the transmission of power, has grown to such enormous proportions that I think the last case on which I had to exercise my judicial faculties was the case of applying the delicate electricity that I knew originally only in connection with the telegraph to the brutal work of rolling mills, which required at certain moments a squeeze of 15,000 H.P. What will be done in the future I do not pretend to prophesy. But what I feel is that no thoughtful man can look upon electricity otherwise than as being capable of dealing with the smallest as well as the greatest tasks of mankind. All that has been done within the last thirty years. And in addition to that there has been a development the future of which it is impossible to foresee, but which was not dreamt of, I think, or prophesied by any other person than by the great James Clerk Maxwell. James Clerk Maxwell realised the vibrations in the electromagnetic field ; he pointed out that they were capable of explaining light, and he left the theory of those vibrations in such a perfect state that when that much-lamented genius Hertz discovered the Hertzian waves it came to all those who had studied mathematical electricity only, as it were, as the fulfilment of a prediction. I do not know what

that is coming to, but as far as I can see in a month or two we shall find from the Eiffel Tower British time shouted all over the world. Such are the practical developments which I have lived through. But there are triumphs equally great in the unpractical world. Electricity used to be looked upon as a kind of luxury in which the material universe occasionally indulged. It was always contrasted with chemical action, with mechanical action. But while it has been developing its power in the industrial world, it has also been showing that it is probably the secret cause and the unknown guide of all the changes that go on throughout the universe. The chemist speaks of it with deep respect, and generally with profound ignorance. The man who tries to investigate the mysteries of matter is beginning to think that not only is electricity an important agent, but really he is inclined to abandon the theory that matter exists, and looks upon it as a kind of stolid form of electricity.

When I knew this body first it was the Society of Telegraphic Engineers. Soon a sort of revolt came, and the next time I remember seeing the name it was the Society of Telegraph Engineers and Electricians. Now this has blossomed into a still more sonorous title. You feel that your world has increased, and therefore that it is a proper occasion to change your name.

With this last toast I have the honour to couple the name of the President, Mr. S. Z. de Ferranti. In the early days he was one of the first to appreciate the possibilities of electricity. He saw how great it would grow up. The only complaint I have ever heard of him in my life is that he had such a high opinion of the little baby that he wanted to breech it too soon. Of all those that I have met, I know of no man whose imagination and foresight was clearer. He always knew how great a thing electricity was to be. And, remember, I have met him in all connections. I have met him as friend, I have met him as foe ; I have met him when he was teaching me, I have met him when I unsuccessfully tried to teach him ; and all I can say is that, whether in the courts or whether out of the courts, wherever it has been, his clearness of thought, his knowledge, his power of invention (and there I am not referring to the courts !) and his courtesy have distinguished him and made him always one of those figures that I like to call back to my mind and think of as a representative of your great and growing science. You owe much to him. The character of the English nation is that the progress it makes it never lets go, but it is not always the first to see the possibilities of things. Therefore a man like your President was a man not only wanted, but, I am happy to say, valued among the electricians of England. And it was not only for his mental qualities that he was so esteemed and so much cherished. It was also from the charm of his manner and person which I think all who know him will say was unrivalled. Gentlemen, I propose the health and future prosperity of your Institution, coupling it with the name of your President.

The PRESIDENT, Mr. S. Z. DE FERRANTI : I must first of all thank

Lord Justice Fletcher Moulton for the very kind way in which he has referred to me in his brilliant speech this evening. I must, secondly, thank him for the most interesting discourse which he has given us, and for the way in which he has taken us back to the past and to the beginnings of electricity, with which he has had so much to do.

Let me first of all speak to you about the Institution. Since our last Dinner, more than a year ago, the most important event that has happened, so far as the Institution is concerned, is that we have now come into possession of our new home on the Embankment. The building, as many of you know, is a fine one, and is fitted up in such a way as to be exceedingly useful for the purposes of this Institution. But, seeing the importance of the interests which we represent, and of the work which we most assuredly do in the interests of electricity, those premises are none too large and none too good for what we have to do with them. With regard to the Institution itself, as you know, it is growing rapidly, and the attendance this evening is a sign of its great growth, as we are four hundred strong to-night, as against about three hundred in former years, or, perhaps, it is a sign of the more general interest that is being taken in electricity, and in our proceedings especially. Now that we have settled down to work in our own building, we have a considerable load off our minds in that direction, and we can, therefore, turn to consider other things concerning the conduct of the Institution—what it should endeavour to do in the interests of electrical science, and what it should also endeavour to do for the benefit of the interests of its members. I am afraid it is thought by a good many that the Institution is not as useful as they think it ought to be in regard to themselves. Some say, "What is it worth to me to belong to this Institution? What good has it done for me?" Well, gentlemen, I can only say that there is a very definite, and I think satisfactory, answer to that question. This Institution would not have rapidly grown to a strength of over six thousand members unless it were of some use to those who belong to it. But this does not say that the Institution might not possibly be more useful in many directions than it is, and what I wish to assure you is that that question is occupying our most earnest attention. It may be considered, and it is perhaps justly said by some, that this is a purely scientific Society; but science is much bound up with other things, and I am very doubtful as to whether what I have just said is the meaning of the constitution of the Institution of Electrical Engineers. If you look into the Articles you will see that it is, broadly speaking, to further electrical interests. Now those are many and diverse, and it is the very diversity of those interests which has made people connected with the Institution, Members of Council, and former Presidents, afraid of dealing more definitely with this subject, because it seemed impossible to legislate beneficially for or affect the different interests concerned. But that is not my view. Personally I think there is but one interest. There are no divergent interests in the industry and in the things it is connected with. What we want is progress and

prosperity. The prosperity of one section will react beneficially upon the other. I am sure there is much good work that can be done and that should be done, and I can only say that I have every confidence that a careful, possibly lengthy, consideration of this subject, may result in our being, as an Institution, able, I hope, to do more for the individual and more for the progress and prosperity of all branches of the industry.

With regard to the present condition of electricity in this country, I cannot say that I look upon it as satisfactory. There is much that we should wish to be different. I have thought over this question, and no doubt many of you have thought over it, and wondered why it was that, notwithstanding the great progress that we have made, the great works that we have and carry on, electricity was not generally more satisfactory in the way of the return furnished by it for the work done, and the money expended upon it; why, in fact, there was not a higher level of prosperity considering what electricity was, the benefits it conferred, and all its numerous possible applications.

In considering that matter I would call your attention for one moment to other great industries. Take, to begin with, the railways. There was great opposition to the introduction of railways in this country. Fortunately this country was practically the first to start railways. Things travelled much more slowly in those days, and the harm which that opposition would have done was limited. But railways were such a great thing that they triumphed, and we were the nation who first made railways practicable. With what result? Gentlemen, the result was that we built the railways and the railway material for the world, and that continued for a long time. That was the result of our getting in first; that was the result of railways not being killed before they had a chance to live properly. Take another very similar case. We started the great textile industry in this country. That was a thing which, not wanting concessions, not wanting public rights-of-way, not wanting powers of Parliament, was not affected in such a way as to be prejudiced, as to be retarded, as to be practically killed. The textile industry flourished; it became a very great thing; we became the textile producers of the world. Later on we not only produced textile material, but as other people were beginning to do some of the textile work for themselves we furnished practically the whole of the machinery for the world's requirements. That is a second great industry.

Now take another, not so great as either of those, but still of immense importance—the motor industry. What do we see there? I believe, to be correct, that the first steam omnibus was a conveyance run between Paddington and the Bank about the year 1834. Just picture this to yourselves, and think of what has happened since. That was a case where vested interests and various other interests brought to bear upon it effectively killed the industry. We were the pioneers: we had started the thing; we might have had the trade of the world. In their wisdom the people killed it. A number of years

went by and mechanical traction remained dead. Eventually it was taken up in Germany, and immensely developed in France, and France became the suppliers of the road traction machinery of the world. We have had millions of pounds worth of motor-cars and the like from France, whilst we have had unemployed workmen walking about our streets. Further, we had not only to buy from France and the Continent the whole of the motors we wanted for the first few years, but we were not doing the world's trade in them as we have been in supplying the material for the railways and the machinery for the textile industries. I have referred to three great industries, and you see the immense benefits that the two which managed to get through without interference, and which survived, conferred upon us in adding to the wealth of the country. But the third one was killed—there is no other way of looking at it—absolutely killed, and the result was that we were out of the business, and had to go to other countries for our requirements.

Now take the case of electricity. In this country there were pioneers, and there was the best of work done in the very early days. But what had electricity to face? There was one thing which we could not complain of, certainly, and that was a well-established and most prosperous gas industry. That was fair competition which would have to be met in any case, but it puts us at a great disadvantage in relation to countries like America, Switzerland, France, and Germany, when there was much less competition in the way of established gas industries. Those countries in consequence were able to progress and develop by continued practice in the application of electricity in a way which was altogether beyond our reach. They became very skilled, very expert, and very successful in the production of electricity and all the things connected with it. There was another thing which adversely operated against electricity in this country, the municipal idea, which is largely tied up with the idea that no one shall make a profit out of anything—it is to be for the good of the people. Granted, the good of the people is right; but I contend that it has not served to a very great extent the good of the people. I contend that in many ways it has done far more mischief than good. We have it established now on good lines, but what was the effect of it in the past? It was this: Lord Justice Fletcher Moulton has called your attention to the fact of there being six barren years in the development of electricity in this country, whilst the other competing countries, our neighbours, were going rapidly ahead and strengthening their position by increasing their knowledge and resources with regard to electrical matters. The municipal idea of no promoters being allowed to make a profit, and of the thing being kept for the benefit of the municipalities, retarded us, and it is impossible for us ever to know what we lost in the way of world position in electricity in consequence. Then there was another sad thing that occurred which stopped our progress in a very unfortunate manner—the Tramways Act. The tramways originally, as regards development, were badly treated in this country.

W en horse traction with cars on wheels was started, there were grea difficulties experienced in getting concessions. The whole thing was grudgingly done; in fact, the tramways were hardly given a chance to live. These companies who had even these poor concessions managed to go on, and many of their concessions had not run out when electrical tramways should have been started in this country. The companies themselves had not the power to put down electric traction. The municipalities who wanted the undertakings would not help them, or, at any rate, that was so in the majority of cases, and the result was that the introduction of electric traction into this country was very greatly delayed. What was the effect of this? The Continent and America got immense practice in this art whilst we were doing nothing, with the result that they were given an immense start, an advantage over us, and we were handicapped without good reason, and much to the detriment of the prosperity of this country. How were the people served in this way by cutting off natural industry, by cutting off possible manufactures in this country, simply with the idea that the municipality must have all there was in it, and that individuals must not make a profit out of the people? Those are things of the past. But, unfortunately, they have left their mark, and I think they are largely responsible for electricity not being in a far more advanced and prosperous condition in this country than it is. I do not want to belittle in any way all the good work that has been accomplished; I do not want to belittle our electrical advancement and progress, the goodness of our machinery, the fineness of our installations, the cheapness with which we generate; but I say that if we have been capable, under these handicaps and disadvantages, of doing this, what should we have done if we had had a fair chance?

We must take things as they are. We must set to—not that we have not already done it to a large extent—ever afresh and see how we can overcome the difficulties and disabilities which the past has imposed upon us, how we can make electricity progress; how we can make the industry more prosperous, and therefore more beneficial to all concerned in it. It is not selfish if we think of it in the light of it being beneficial to our good selves of the Institution of Electrical Engineers, because I am quite sure that any electrical progress that is made will be to the immense benefit of the country at large. I think the position is summed up in this manner: there must be no idea that the municipality is hostile to the manufacturer, or that the manufacturer is trying to take an unfair advantage of the municipality. There must be a cessation of this fatal idea of no profit or a bare livelihood to be got out of electricity. That does no one any good. How are the suppliers of electricity, the great corporations, the municipalities, the public companies to benefit by getting their machinery at bed-rock prices if it creates an impoverished electrical industry? What is the effect of an impoverished electrical industry? It means this, that there is no money available for spending on those great experiments which alone can carry us to a

cheaper generation of electricity, and the knowledge for the more general use of it. Where is the money for these developments to come from if the industry is to be starved by being beaten down to practically no profit in its work? I say, and say it most emphatically, that there could be no greater injury thrown upon the buyer and user of electrical machinery than this idea that you must buy in the cheapest market. Again, the idea of absolutely unlimited competition on prices alone, as we know it to-day, is wrong from every point of view. Why not look somewhat in another direction, and all of us influence those who can help? Why not look at it more from the point of view of a competition of excellence? How little else is there done in most of the specifications that are issued except to try and beat everybody down to the dead level of, I might almost say, Trades Unionism. We are told by Trade Unionists that they do not level down, that they level up. That is the difference then. But I say, why attempt this beating-down process where we could gain so much more by making a competition of excellence, so as to get a better article and an article which people who buy things to make money from, know is the right principle to adopt—something that will pay in the long run, something that will be best over a period of years?

Gentlemen, I have kept you long enough, and I only wish to say this to you in conclusion. If we can get more reasonable ideas; if we can follow either the course I have suggested or some other course which will put electricity, and all matters connected with it, on a really sounder basis, then surely there will develop a thing I spoke to you about not so very long ago—the all-electric idea. I am sure that that is not a thing in the very far distance. It is the thing which, the moment we obtain only a little more knowledge, will make us progress all the more rapidly towards the ideal which I laid before you. If we can do anything to bring that about I am sure that we shall have secured prosperity for this Institution, prosperity for its members, and vast benefit and good to the country at large.

Mr. Sam Mavor, in proposing the toast of "Our Guests," said: Mr. President, my lord and gentlemen, I believe I owe the pleasure of being permitted to propose this toast to the desire of the Council to associate as far as possible the Local Sections of our Institution, and I am sure that will be greatly appreciated by the Local Section of Glasgow, which I have the privilege to represent. We have a wide and ever-widening field from which to draw our guests. The activities represented by our Institution affect, as Lord Justice Fletcher Moulton so eloquently said, nearly every field of our national life. Statesmen, administrators, the navy, the army, commerce, industry, civic, social, and domestic life are all in a growing degree affected by the application of electromagnetic phenomena. We have among us to-night many old friends and some new ones. To our great pride, we are entertaining among our guests several of our own members as distinguished representatives of other spheres. Lord Justice Fletcher Moulton, as he has already said, is one of our oldest members, and it is interesting to know that

in his early gladiatorial days he won much of his distinction, and all our admiration, in cases of special interest to our profession. Another of our members whom we have the honour to entertain to-night, is Mr. Alexander Siemens, President of the Institution of Civil Engineers, whom we congratulate on having attained the blue riband of the engineering profession. We have also with us to-night representatives from the daughter nations over seas; of the naval and military service; of many kindred societies, and others associated with public life. I have the further pleasure of associating with this toast the name of Mr. Leonard Stokes, the President of the Royal Institute of British Architects, whose name is almost a household word in this country, and is identified with many of our most notable public buildings.

Mr. LEONARD STOKES (President of the Royal Institute of British Architects) responded on behalf of the guests.

JOURNAL

OF

The Institution of Electrical Engineers.

Founded 1871. *Incorporated* 1883.

VOL. 46. 1911. NO. 207.

Proceedings of the Five Hundred and Fifteenth Ordinary General Meeting of the Institution of Electrical Engineers, held on Thursday, January 26, 1911—Mr. S. Z. DE FERRANTI, President, in the chair.

The minutes of the Ordinary General Meeting, held on January 12, 1911, were taken as read, and confirmed.

The list of candidates for election into the Institution was taken as read, and it was ordered that it should be suspended in the Hall.

The following list of transfers was announced as having been approved by the Council:—

TRANSFERS.

From the class of Associate Members to that of Members—

George Henry Gibson.
Frederick John Holmes.
Andrew Home-Morton.
Walter Hudson.
Wilmot Ernest Lane.
Gustavus F. Moller.
Noel Burn Rosher.

From the class of Associates to that of Members—

Rupert Stanley Allen.
Louis Boniface Wilmot

From the class of Associates to that of Associate Members—

Eustace R. Conder.
Henry Montagu Lyons.
Lieut. Clement E. Vines, R.A.

From the class of Students to that of Associate Members—

Arthur Barratt.
William Leighton Chubb.
Lionel H. C. Dermer.
Reginald Glanfield.
Birendra Chandra Gupta.
James Park Hacking.
Robert H. F. Houstoun.
Thomas Moore Kirkby.
Lionel John Lepine.
Marcus MacDonald.
Arthur C. Morrison.
Augustus R. P. Price.
Frank Shaw.
Frank W. Timmis.
Harold Edgar Webb.
Louis Theodore Young.

Messrs. F. N. Haward and A. P. Haslam were appointed scrutineers of the ballot for the election of new members, and, at the end of the meeting, the following were declared to have been duly elected :—

ELECTIONS.

As Members.

Harry Augustus Couves.
Sydney Bryan Donkin.

As Associate Members.

John Alsing.
Francis Herbert Briggs.
Tringad Knight Evans.
Frederic William Francis.
William Henry Freemantle.
James Wilkinson Heaney.
Duncan Fraser McIntosh.
Francis McMorrough.
Edward Ernest Moore.
Edgar Williams Newton.
Patrick Alfred Paris.
Thomas Duncan Parry.
George Richman.
George Rogers.
Walter Richard Rothenberg.
William Verity Ryder.
Robert Page Stewart.
John Duncan White.
William Norman Wilson.

As Associate.

Rowland Lewis Goold.

As Students.

John Vivian Buckley.
Richard Cowell.
Douglas Harold Green.
Daniel Harrop.
Frederick Cecil Heayberd.
Stephen Holmes.
Leon Pierre de Graaff Hugo.
Philip Sydney E. Jackson.
Ernest George James.
Leonard Seth King.
Madhav L. Kshirasagar.
Bernard Samuel Lion.
Rashbehari Nandi.
Alexander Neilson.
James Frederick Perrin.
Cyril Ernest Robertson.
Hugh Dunkerley Shaw.
H. Cecil Simmons.
Douglas Horace C. Smith.
Norman Stell.
Kenneth Alderson Ward.
William A. Woodrow.

Donations to the *Library* were announced as having been received since the last meeting from Blackie & Sons, Ltd., The Board of Education, Dr. H. Borns, Crosby Lockwood & Sons, A. G. Ellis, E. Gerard, E. G. Hiller, J. Mascart, J. Poole, S. Rentell & Co., Ltd., The Executors of the late Theophilus Smith, The Smithsonian Institution, E. and F. N. Spon, Ltd., Svoriges Allmanna Exportforening ; to the *Museum* from the *Daily Telegraph*, Major W. A. J. O'Meara, C.M.G., Siemens Brothers & Co., Ltd., Sir Joseph Swan ; to the *Building Fund* from B. Balaji, H. C. Channon, S. E. Glendenning, H. Hirst, A. Hutchinson, Sir H. B. Jackson, H. W. Kolle, C. F. B. Marshall, Professor J. T. Morris, W. R. Rawlings, J. H. Rosenthal, M. Solomon, Sir Joseph Swan, H. W. Turner, T. C. T. Walrond, A. Wright, H. W. Young ; and to the *Benevolent Fund* from H. Alabaster, O. H. Bishop, I. Braby, A. Denny, W. Duddell, S. Evershed, F. A. Greene, D. Henriques, H. Hirst, S. H. Holden, W. Judd, H. W. Kolle, E. de M. Malan, Sir H. C. Mance, C. F. B. Marshall, C. H. Merz, C. C. Paterson, W. R. Rawlings, S. G. C. Russell, F. Smith, J. B. Smith, A. P. Trotter, R. J. Wallis-Jones, T. C. T. Walrond, W. A. Walton, J. G. Wilson, and C. H. Wordingham, to whom the thanks of the meeting were duly accorded.

The following papers : (1) "Modern Long-distance Transmission of Electrical Energy," by Mr. W. T. Taylor (page 510), and (2) "Extra-High-pressure Transmission Lines," by R. Borlase Matthews and C. T. Wilkinson (page 562), were read and discussed, and the meeting adjourned at 9.45 p.m.

MODERN LONG-DISTANCE TRANSMISSION OF ELECTRICAL ENERGY.

By WILLIAM T. TAYLOR, Member.

(*Paper received November* 7, 1910. *Read before the* INSTITUTION *January* 26, 1911; *before the* NEWCASTLE LOCAL SECTION *January* 30, 1911; *before the* MANCHESTER LOCAL SECTION *January* 31, 1911, *and before the* YORKSHIRE LOCAL SECTION *February* 15, 1911.)

[In the absence of the Author in South America, the paper was read on his behalf by Mr. J. F. C. SNELL, Member of Council.]

As a notable example of long-distance transmission to a small consumer the Central Mexico Light and Power Companies have recently constructed a steel tower line 78·5 miles for an operating voltage of 100,000 to the city of San Luis Potosi, which is approximately 200 miles from the nearest generating station, the maximum load at the present time at this receiving end being 1,200 k.w. Before entering into the contract it was thoroughly worked out by the company's engineers in Mexico and in Colorado (Central Colorado Power Company), who found that the proposition was a paying one. Of course, this was not the only thing the company had in view before going in for a concession and an expensive transmission line and sub-station; nevertheless, it was the only consumer at the time. Since then another receiving station has been developed at San Filipé.

Not long ago—during the time much discussion was going on about developing an hydro-electric power system at Victoria Falls—quite a number of engineers were in favour of high-voltage *direct-current* transmission. As regards the transmission line only, one realises that there is much in favour of direct current, as for instance:—

(*a*) Insulators and strength of towers are reduced to a minimum.
(*b*) The number of conductors is reduced to two at most (probably only one if a grounded return is used).
(*c*) The number of insulators is reduced, and consequently there is less opportunity for breakage and interruptions.
(*d*) Size of insulators reduced to 30 per cent. of those corresponding to the maximum alternating-current voltage.
(*e*) Power factor of the line unity.
(*f*) Self-induction of the line reduced to zero.
(*g*) Charging current of the line reduced to zero.

The drawback of the high-voltage direct-current system is the complication at the generating and receiving stations, otherwise it would probably become universal practice. Probably the day is near at hand when direct-current long-distance transmission systems

will be made as simple as the present day high-voltage alternating current long-distance transmission plants.

In considering the general feasibility of a long-distance transmission system the engineer is first called upon to furnish the data upon which the design, construction, and operation will be based. It is very important that accurate estimates of the earning power of the project should be made. Factors such as government contracts, future extensions, legislative limitations, and general legal matters are generally left to the financial administration.

In considering the transmission line only there are few conditions except the distance and the amount of power to be transmitted that limit the feasibility from a financial point of view. Of course, conditions such as passing over a mountain covered throughout the year with snow and subject to dangerous slides, or crossing a dangerous and expansive jungle, affect the conditions of transmission, the economy of any line being taken as the ratio of annual expenditure to the total receipts from the system.

Two of the most interesting factors in the transmission of electrical energy to be taken into account are those of (*a*) line-drop (regulation) and (*b*) the size of conductor necessary for a given drop. They are closely related to each other, and depend upon the line voltage.

Experience has shown that the weakest link in a long-distance transmission system is the line itself. Whatever the source of power may be, and however good the mechanical and electrical construction, the line will be subject to all sorts of accidents to which none of the apparatus and equipment on the system is liable. It will be exposed to rough atmospheric conditions, and open to malicious interference by the wilful breaking of insulators and short-circuiting of the lines through pieces of wire, branches of trees, and other articles thrown across the line.

It is sometimes found that the increased cost of apparatus necessary for increasing the transmission voltage is not counterbalanced by the saving in copper, and even where the saving justifies a higher voltage it is important to inquire into the possibilities of trouble from the use of a higher voltage. This is especially the case in severe climates, as, for instance, near the sea or in snow-bound regions. In such climates there may be more frequent interruptions of service and the extra expense of maintenance as result of punctured insulators, extra patrol houses and patrol men, and probable extra installation of line switches, may be greater than with the use of a lower voltage.

Under some conditions, as found from experience, it is much better to adopt a lower voltage with more line copper, or an extra heavy insulator designed for 110,000 volts but only used for 60,000 volts, than to run the risk of repeated interruptions.

The ratio of the leading or lagging currents can be controlled by adding electrostatic capacity (condensive reactance) to the line in the form of synchronous generators, preferably at frequent intervals along the line, or by adding inductance (inductive reactance) by the use of

non-synchronous apparatus. Condensers may be connected across the line, or inductance coils may be connected in series with the line, in which case they may be switched in or out, one or more at a time, as the desired balance with change of load is found necessary.

As a transmission line has both resistance and reactance, the voltage at the receiving station will change with every variation of load, because a certain portion of the voltage at the generating station is absorbed in maintaining the current in the line, and as the current varies with the load, the voltage drop in the line will vary, and either the voltage at the generating station or that at the receiving station must change. In practice it is always sought to keep the voltage at the receiving station as constant as possible, which may be accomplished by changing the voltage at the generating station in proportion to the varying load. This may also be accomplished by changing the power factor to compensate for the variations in the drop of voltage.

In the case of lightning discharges, the frequency may be thousands or even millions of cycles per second. In the case of switching, arcing, grounds, etc., the changes in voltage are practically instantaneous on those parts of the line nearest to the point where the switching or grounds occur.

So far as further increase in voltage is concerned for transmission lines, it appears to be limited by the production of corona. A very few years ago the limit was based on the line insulator, and previous to that period the power transformer was the limiting element. It is possible that the limits imposed by the corona (which depend on the diameter of the conductor used, the distance apart of conductors, the voltage impressed on the line, and the average atmospheric conditions) might prove to be a considerable factor in the choice between copper and aluminium transmission lines, aluminium having for a given resistance per mile a 30 per cent. larger diameter than copper. In order to reduce this corona it is necessary to increase the outer diameter of the copper conductor or to substitute copper tubing for solid copper.

To reflect and check surges on transmission lines choke coils have been used to some advantage for many years back, their effect being measured by the value of inductance and insulation. If the inductance of the coil be of small value a corresponding reflection will take place, thus allowing the surge to pass through the coil and continue to the apparatus beyond. A better way of protection is afforded by using both choke oil and extra heavy insulation on the entering turns of the high-voltage transformer.

The lightning arrester is advantageous for the protection of apparatus from surges when set correctly. The effect on the line caused by a flash-over of the lightning arresters may cause a heavy disturbance on the whole system, since the reaction set up tends to increase the current on the line in proportion to the square of its original value. The higher the voltage the less will it be affected from this cause on account of the smaller current flowing for any given amount of power.

In the early days of long-distance transmission work the formulæ used for the calculation of line reactance, self-induction, capacity, regulation, and amount of copper necessary for a given drop, were very tedious. In fact, it is only within the last few years that transmission line calculation has been simplified, and applied by the transmission engineer to actual conditions. The author calls to mind his experience some years ago when connected with the California Gas and Electric Corporation, which had at that time a few hundred miles of 60,000-volt transmission line, and the then method of calculation for line reactance, size of wire, capacity, regulation, etc. Although the general formulæ used were long and occupied a great amount of time, they were surprisingly accurate for all practical purposes.

To all those not familiar with the old formulæ it may be of interest to know how the early transmission engineers got their results. Generally they had some physical data at hand, such as the kilowatts to be transmitted, the voltage of the line, spacing of wires in feet between centres (wires being set at the points of an equilateral triangle), distance of transmission in miles, assuming a power factor and percentage loss of an average value. From these data the size of wire, self-induction, capacity, and charging current could be calculated, and finally a diagram made of the regulation of the line.

The percentage loss of the delivered load at the end of the line was found from the expression :—

$$P_{(copper)} = \frac{3\,R \times 100}{W} \times \frac{W^2}{3\,E^2 \cos^2\phi} = \frac{D\,W \times 10{\cdot}8 \times 100}{C\,M \times \cos^2\phi \times E^2}$$

$$P_{(aluminium)} = \frac{3\,R \times 100}{W} \times \frac{W^2}{3\,E^2 \cos^2\phi} = \frac{D\,W \times 17{\cdot}4 \times 100}{C\,M \times \cos^2\phi \times E^2},$$

the conductivity of aluminium being taken as 62 per cent. that of copper; E being the voltage at the end of the line, W the kilowatts delivered to the end of the line, R the resistance of one wire, cos ϕ the power factor of the load, D the distance of transmission in feet (one way), C M the area of conductor in circular mils, and the constant 10·8 for copper the resistance of 1 mil-foot.

Substituting C M for P, the size of wire, for copper, is—

$$C\,M = \frac{D\,W \times 10{\cdot}8 \times 100}{P \times \cos^2\phi \times E^2};$$

and for aluminium—

$$C\,M = \frac{D\,W \times 17{\cdot}4 \times 100}{P \times \cos^2\phi \times E^2}.$$

The self-induction of one wire was taken from the formula—

$$L = \frac{1}{\sqrt{3}} \times 0{\cdot}000558 \left(2{\cdot}303 \log_{10} \frac{d}{r} \times \frac{1}{4}\right) \times \frac{D}{5280};$$

where—

L is expressed in henries.
d is distance between conductors in inches.
r is radius of conductor in inches.
D is distance of transmission in feet (one way).

The formula for capacity of one conductor, expressed in microfarads, was—

$$C = \frac{0{\cdot}0776 + \frac{D}{5280}}{2 \log_{10} \frac{d}{r}}.$$

The charging current was then obtained from the expression—

$$I_c = \frac{CE \times 2\pi f}{\sqrt{2} \times 10^6}.$$

Power component, from I cos ϕ; and the wattless component, from I sin ϕ.

The drop in voltage due to the power component of the load was expressed as—

$$\text{Resistance drop} = + I \cos \phi \, R,$$

and—

$$\text{Reactive drop} = - j I \cos \phi \, L \omega.$$

The drop in voltage due to the wattless component of the load current, as—

$$\text{Resistance drop} = + j I \sin \phi \, R,$$

and—

$$\text{Reactive drop} = + I \sin \phi \, L \omega.$$

The voltage drop due to the charging current, as—

$$\text{Resistance drop} = - j \frac{I_c \times R}{2},$$

and—

$$\text{Reactive drop} = - \frac{I_c \times L \omega}{2}.$$

A diagram was then made from the above data, something after that shown in Fig. 1.

For a number of years past it has been generally known that the capacity current taken by the line raises the voltage at the receiving station above that at the generating station, the increase being more marked the greater the capacity current and the longer the transmission. It has also been known for many years past that a reduction in the frequency will reduce both the charging current and the inductance of the line, also changing the size of line conductors, or increasing or decreasing the spacing of conductors of the line will have but very little effect on the charging current and inductance.

On long-distance and important systems (such as 100,000 k.w. at 135,000 volts), a condition to be expected in the near future, the author is of opinion that split conductors will be employed—that is, two or more conductors constituting each phase of the transmission system. These conductors will be supported on separate insulators throughout

the entire length, and only connected in multiple by means of switches at such points on the line as will facilitate continuity of service.

By such an arrangement the electrostatic capacity of the entire line would be increased and the inductive reactance decreased, and interruptions of service from any cause reduced to a minimum. The flexibility of the system would be the most reliable that could possibly be obtained, as separate and independent loads would be carried over each set of conductors, and under ordinary conditions of load the regulation of the system would be greatly improved.

Of course, such an arrangement is not unlike our present transmission lines when run in duplicate, tied together where experience finds convenient and sectionalised at important points. Although the arrangement of existing transmission lines, taking the largest and

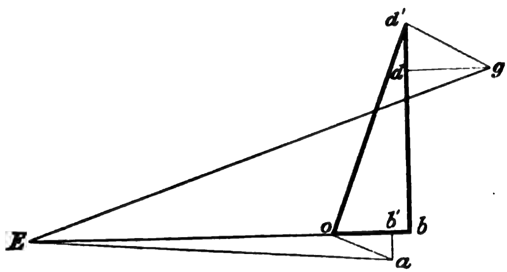


FIG. 1.—Regulation Diagram.

E a = voltage at the generating station.
E g = voltage at the receiving end when delivering full load.
o a = resistance drop due to power component.
b d' = reactive drop due to power component.
d d' = resistance drop due to wattless component.
d g = reactive drop due to wattless component.
a b' = resistance drop due to charging current.
o b' = reactive drop due to charging current.

longest, are important and noteworthy, the author believes that the very near future will see developments where branch lines will be longer than the present longest main lines, and generating and receiving stations will be far larger than those in existence. The longer and more important transmission lines become, the nearer an approach will be made toward the arrangement of split conductors, either separately insulated or brought together on one insulator. The former is the better and more flexible method.

In the operation of transmission systems it is most important to keep good regulation. It is impossible to give satisfactory service unless the fluctuations of voltage can be kept within the limits of from 3 to 8 per cent., depending on the size and length of transmission system and the character of load. With large non-synchronous motors carrying unsteady loads, such as 5,000 to 7,000 H.P. for rolling mills,

and motors of 1,000 to 1,500 H.P. for hoisting purposes, it becomes a difficult problem to keep the voltage within any reasonable limit when this character of load is at the end of a line 200 miles from the nearest generating station, and when the units at the generating station are only of moderate size. By moderate size is understood, say, 3,500 k.w. A receiving station carrying a city lighting load and

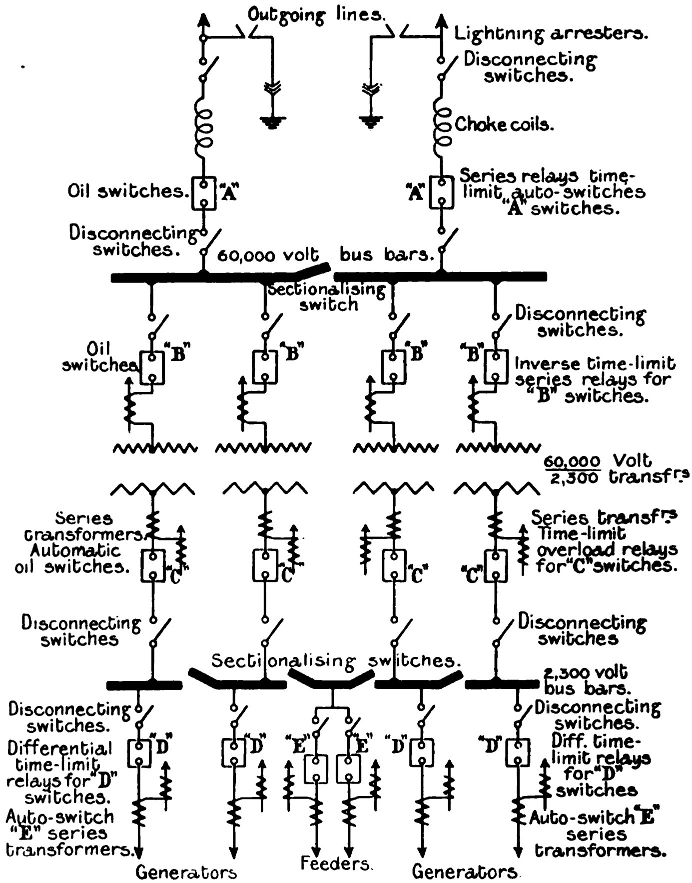


FIG. 2.—General Lay-out of a 60,000-volt Generating Station.

fed from the same transmission line will be greatly impaired if the fluctuations of voltage are above this value.

The line energy taken by the condensive reactance will vary as the square of the voltage, and the energy taken by the inductive reactance will vary as the square of the current. Therefore, when the condition

of balance is reached, as would be the case when the leading and lagging energies are neutralised—

$$\frac{E}{I} = \sqrt{\frac{X_s}{X_c}},$$

taking the leading energy as $X_c E^2$, and lagging energy as $X_s I^2$.

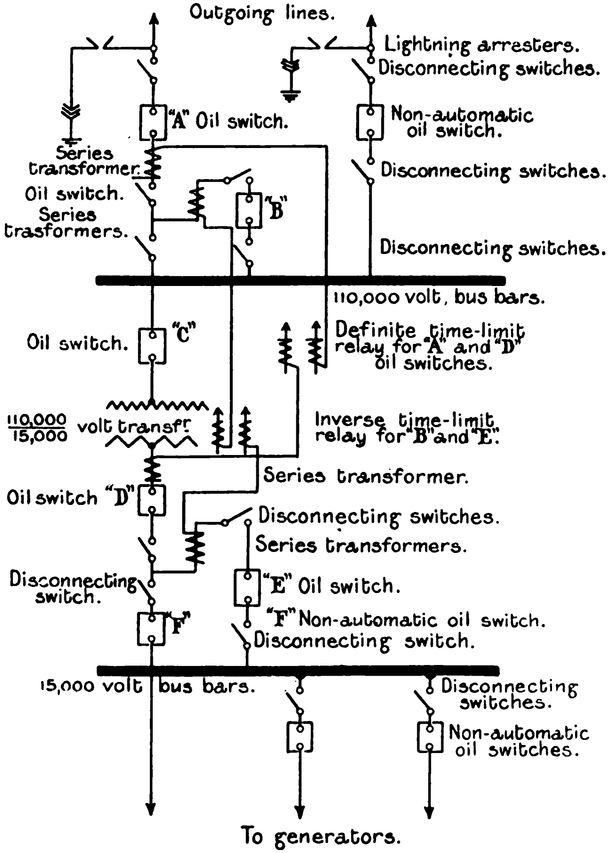


FIG. 3.—Lay-out of One Complete Section, showing Line, Transformer, Relays, and Switches for 110,000 Volts.

Every increase in the amount of power, voltage, and distance, and every additional branch line and receiving station or extension of the main line to a far-off receiving station adds more difficulties and more chances for interruption of service as well as more intricacies. More valuable information and technical data to the engineering profession are, however, thus obtained.

With hydro-electric transmission systems so large as we have good reason to expect within a few years (since Governments are now considering very seriously the natural resources available in their provinces), transmission engineers will do well to make an exact study of present conditions and thus be well prepared for these future possibilities.

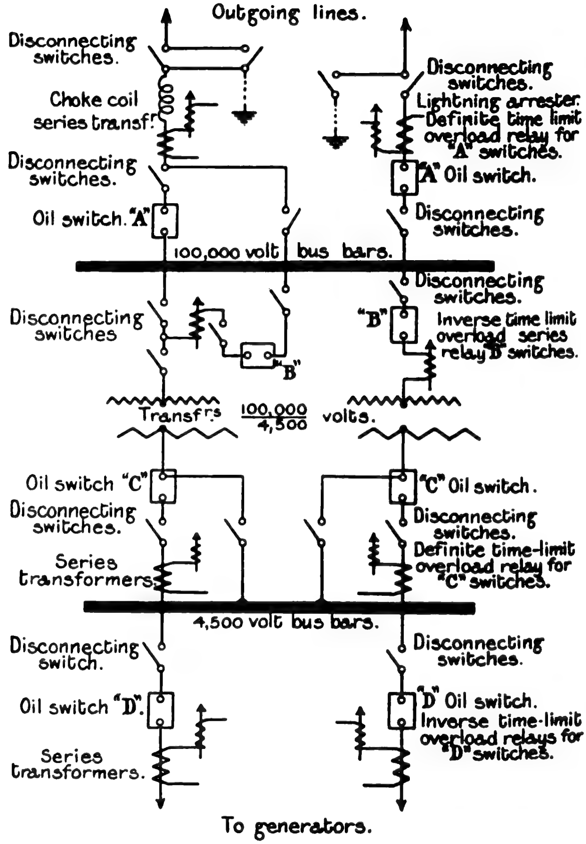


FIG. 4.—Lay-out for 100,000-volt Generating Station.

Systems.—The electrical portion of all long-distance transmission systems may be divided into—

(*a*) Generating and receiving stations.
(*b*) Transmission lines.

(*a*) The electrical apparatus of practically all modern 60,000- to 110,000-volt transmission systems have their generating and receiving

stations arranged to conform, so far as the wiring lay-out is concerned, with either one or a combination of the different schemes shown in Figs. 2 to 10.

The average long-distance system is representative of a class supplying energy to a varied load, consequently interruptions of all kinds

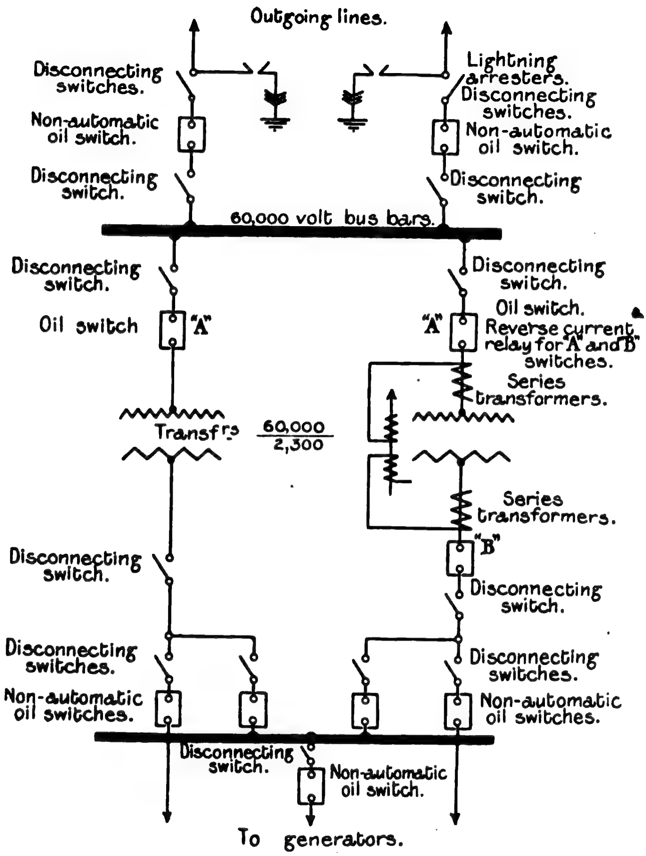


FIG. 5.—Lay-out of 60,000-volt Generating Station.

must be avoided. It may consist of local tramways or railway companies, mines, local power and lighting companies, and also factories, so that reliability of service is a serious question.

Such factors as design, installation, and operation of the equipment which particularly lend themselves to change of machinery and apparatus from one section of busbar to another, or from one transmission line to another, at a moment's notice, is quite as important as the general design and lay-out of the machinery and apparatus. Many

years of experience have shown that the design, installation, and correct location of switches for a generating station, transmission line, and receiving station have a very important bearing on the continuity of service of a large system.

Lately practice has been diverted to outdoor installations of lightning arresters, entering buildings from the roof, and arranging

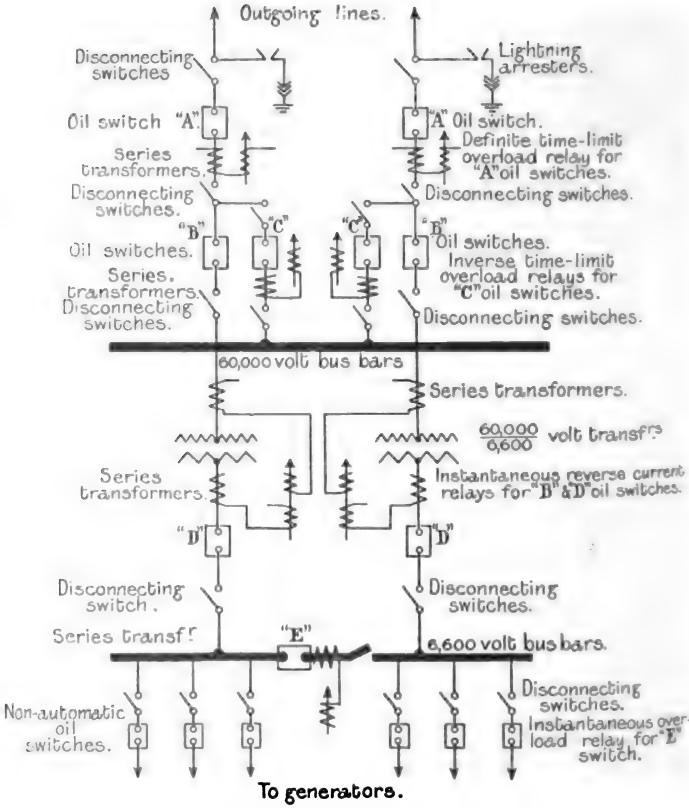


FIG. 6.—Lay-out of a 60,000-volt Generating Station.

high-voltage oil switches in steel tanks similar to high-voltage transformers, and operating them by primary relays, and using the high-voltage oil-switch bushing as the primary for series transformers, thereby cutting down the cost of series transformers by a considerable amount.

It is a well-known fact that in order to operate a long-distance transmission system, it requires considerable generator capacity, even at no load, that is, when the line is absolutely open. As a practical

illustration of this, take the Southern Power Company, U.S.A., which has a 7,000-k.v.a. load on its 100,000-volt lines when all the switches are open at the receiving ends.

Transformers at the generating stations are now usually arranged either in groups of three single-phase or one polyphase for each generator, no matter what the kilowatt rating of the transformer or

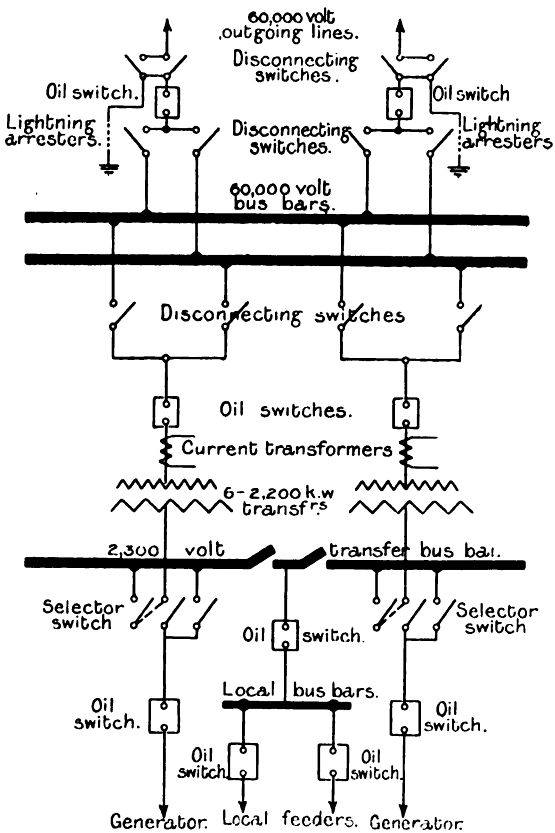


FIG. 7. 60,000-volt Washington Water Power Co. Generating Station.

transformers may be. One of the largest installations of this kind is three 6,000-k.w. single-phase transformers with a 12,500-k.v.a. generator for the Mexican Light and Power Company.

This year has seen a radical change in the design of high-voltage oil switches of 100,000 volts or less. The part containing the oil is of sheet steel similar in every respect to the tank of a high-voltage transformer; it is located on the engine-room floor with its switch

mechanism and relay, and is arranged to operate either mechanically, electrically, or pneumatically. Its adaptability to any location in a generating station or sub-station has simplified the high-voltage wiring lay-out, and consequently cut down the cost of expensive brick walls and barriers, etc. During the early part of the present year, the author

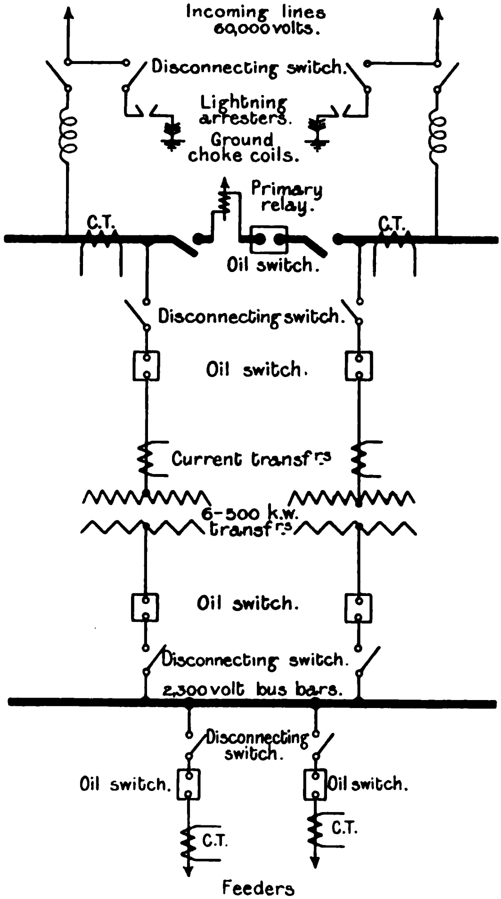


FIG. 8.—60,000-volt Sub-station for Srinagar, Kashmir, India.

had the good fortune to be present at the Schenectady Works (General Electric Company) during the first tests on some 110,000-volt switches of this design. One of the tests with which the author was connected was that of a 100,000-volt electrically operated (primary relay) oil switch for the Mexican Light and Power Company. The switch bushings are of the concentric, compound-filled type, and designed to

fit half-way into the steel tank. The maximum alternating-current voltage impressed on these bushings, *i.e.*, from bushing to ground or tank, was 375,000 volts. One of the most interesting parts of this switch is a new departure in the design of a series transformer which is made to slip over one of the bushings.

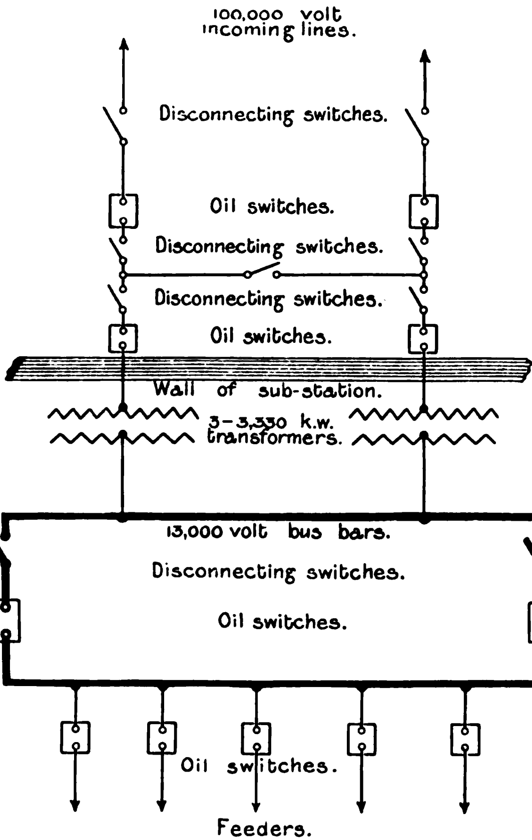


FIG. 9.—100,000-volt Sub-station for the City of Denver.

(*b*) Before making final arrangements for the construction of a transmission line, it is very important to know the location of the generating stations, receiving stations, and their relative distances apart, as well as the atmospheric conditions and altitudes, which have a bad effect on the line when operating at high voltages. While one section of a long-distance transmission line or a branch from the main line may only warrant a single circuit construction, the next section of branch line or generating station may be so important that it becomes

absolutely necessary initially to build a more expensive construction and a double line.

For systems that have their generating stations and receiving stations scattered about in different directions, it is more profitable, from the point of continuity of service, to build a double-circuit con-

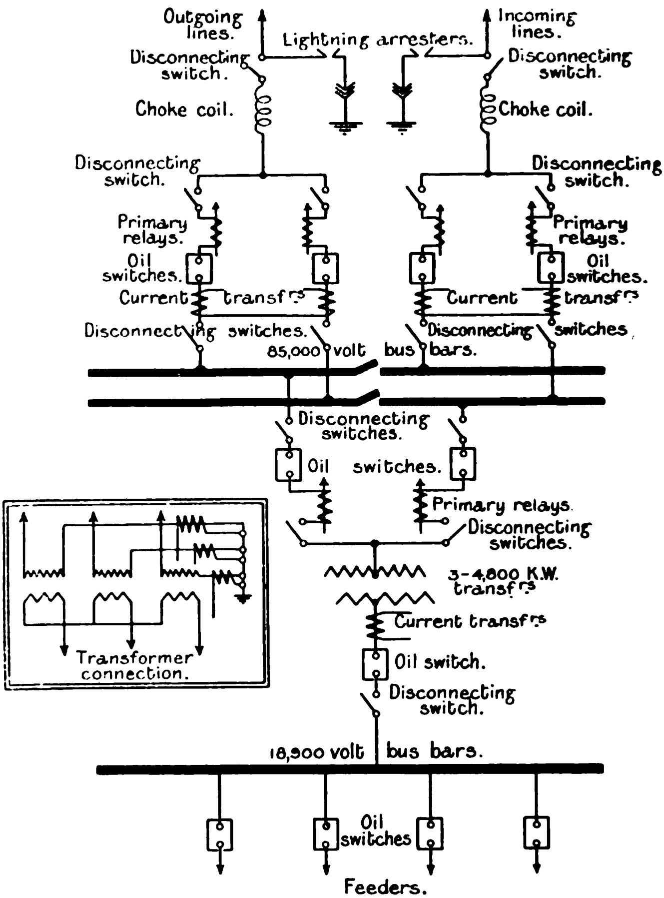


FIG. 10.—85,000-volt Nonoalco Sub-station, City of Mexico, Mexico.

struction to each station (no matter what the character or magnitude of the load it may have at the time) with cross-over and sectionalising switches to be manipulated in case of trouble on any one line or for necessary repairs, etc., also on account of the possibility of future extensions. With a single-circuit construction through part or the whole of the line, it would be impossible to avoid long interruptions

of service should a wire break or the circuit become crossed, as men would first have to locate the trouble before work of any kind could be done; whereas, in the case of a double line, men are at hand to change

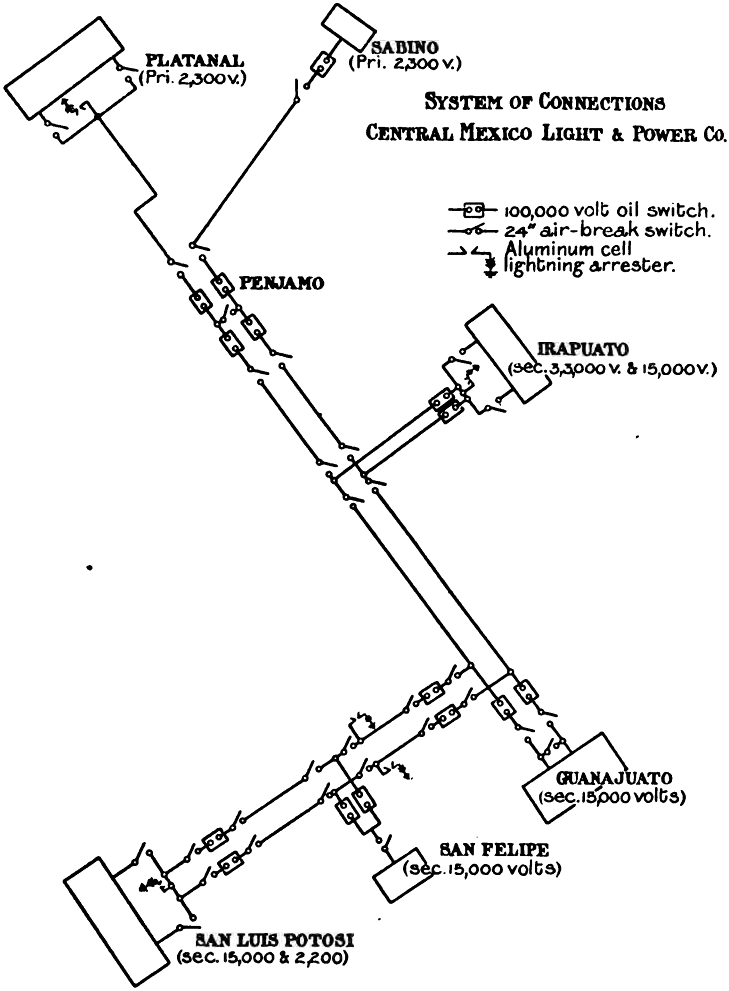


FIG. 11.—100,000-volt Transmission Line Connections.

over at a moment's notice to the good line should the system happen to be operating only over one line at the time. If, however, the two lines are in operation at the time of trouble, one set of sectionalising switches are left open and changed over in the usual way if the trouble is found on the line with the sectionalising switches left in.

With the best mechanical construction and insulation a transmission line will be a failure, so far as continuity of service is concerned, if its general lay-out is not interchangeable by means of sectionalising and cross-over switches conveniently located, and if the location of line be hard to get at for repairs. The simpler the lay-out and construction, the better it will be for patrolling, inspecting, and convenient sec-

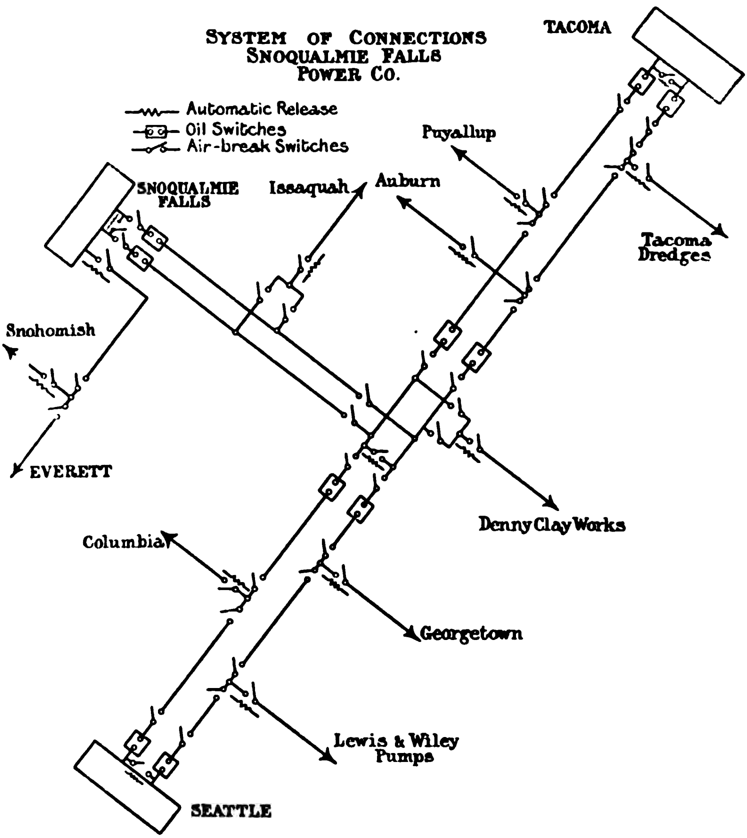


FIG. 12.—30,000-volt Transmission Line Connections.

tionalising in case of trouble or necessary repairs. The exact length of each section will depend a great deal on the roughness of the country through which the line is built, the number of branch lines, and the relative importance of sections. The line switches may be located on the line structures themselves, or a separate switch and patrol house may be built. Figs. 11 and 12 show line arrangements that are giving good service.

Transmission-line Steel Towers and Wooden Poles.—As the price of wood is steadily increasing and the price of structural steel is decreasing, practice is steadily leaning toward steel towers and poles as substitutes for wooden poles and structures. With the use of steel towers longer spans and higher structures can be used, resulting in a less number of insulators and insulator supports. Depending upon the conditions of the country, spans range from 300 ft. as a minimum to 750 ft. as a maximum. On straight-line construction, from 8 to 12 towers are used per mile, the length of span increasing with the height of tower, the height being measured from the ground stub-joint to the first-line conductor, which usually is from 40 to 55 ft.

The fundamental features required to be known in the design of steel towers are :—

(*a*) Topography of the country through which the line is to be run.
(*b*) Character of ground for tower foundations.
(*c*) Number of towers per mile.
(*d*) Arrangement of conductors.
(*e*) Distance apart of conductors.
(*f*) Size of conductors.
(*g*) Whether with or without overhead grounded cable.
(*h*) Facilities for the distribution of line material.

Most tower lines in operation at the present time are using overhead grounded steel cable grounded at each tower. The steel cable is pulled up to the requisite tension and securely fastened by means of a clamp to the top of each tower. This gives a much greater ultimate strength and a much higher elastic limit than the line conductors, and is therefore taken advantage of when considering the design, as it provides an overhead anchorage, enables the line conductors to be assembled with less rigidity, and permits the satisfactory use of a lighter tower. It has the further advantage of providing a means of protection of the line from lightning, and tying together all the towers and connecting them so that all are at the same potential. This is a very essential factor on long lines, even when the current is off, so that work can be safely carried on without danger from shock.

Factory tests of the strength of towers are determined by actual full-load tests. The method of determining the amount of the test loads is to calculate the maximum amount and direction of the effect of the wind, ice, and longitudinal wire tension, and above this amount to add a liberal margin of extra load, which the test towers must stand. In this connection it is interesting to note the result of a few tests made on a tower for the Virginia Power Company.

Test 1.

A pull in the direction of the transmission line applied at the centre of the middle cross-arm.

Pull in Lbs.	Deflection in Inches, taken at Top Cross-arm.
1,000	0·125
1,500	0·250
2,000	0·500
2,500	0·750
3,000	1·000
3,500	1·250
4,000	1·500
4,500	1·750
5,000	2·000
5,500	2·375
6,000	2·625

After release of load, tower returned to 0·5-in. set.

Test 2.

A pull in the direction of the transmission line applied at the end of the two cross-arms on the same side of the tower.

Pull in Lbs.	Deflection in Inches, taken at Top of Cross-arm.
1,500	1·00
2,000	1·75
2,500	2·25
3,000	3·00

After release of load, tower returned to 1·00-in. set.

Test 3.

A vertical load applied to the end of the lowest cross-arm.

Load in Lbs.	Vertical Deflection in Inches, taken at the End of Cross-arm.
500	0·500
750	1·250
1,000	1·875

After release of load, cross-arm returned to 9·75-in. set.

Test 4.

A pull in the direction of transmission line applied to the end of the middle cross-arm, together with a pull at the same point and in the same line, but in an opposite direction. After both pulls were developed, the cable on one side was cut, resulting in the instantaneous application of the opposite pull.

Application.	Deflections in Inches, taken at the End of Cross-arm.
With both pulls applied	0·00
Immediately after cable was cut ...	2·25
Remaining cable strain	1·50
After release of all strain	1·00

Figs. 13, 14, and 15 show the assembly of towers for the pin-type insulator of 42, 49, and 57 ft. respectively. The arrangement of steps on the right side of tower is now standard practice.

Figs. 16 and 17 show a general assembly of a 2-circuit tower with centrally located steel rod extending 36 in. above the topmost insulator to support the overhead ground cable.

The question of depreciation of a steel tower due to corrosion has not yet been definitely determined. Depending on the quantity of galvanising, climatic conditions, and the amount and class of material used, the life of a steel tower should not be less than 35 years when erected in a concrete foundation.

Some time ago it was found necessary to change a few of the towers on the Guanajuato Power and Electric Company's main transmission line and branch line of the Michoacan Power Company, so as to make a simple transfer at this junction, one line being designed for the suspension-type insulator and the other for the pin-type insulator. When the towers which had been fixed directly into the ground for more than 7 years were removed, a careful examination of each tower base could not detect the least deterioration of the towers nor depreciation of the galvanising.

In looking over the various schemes in use up to the present time one finds that transmission-line towers have been built for three, six, and nine conductors, with and without overhead ground cables, the usual practice being one ground cable above the circuit. In some two cables have been used, one above each circuit. The height of the lowest conductor from the ground line varies from 35 ft. as a minimum to 65 ft. maximum height. The spacing of conductors varies from 3 ft. 6 in. for a 33,000-volt line to 10 ft. for a 110,000-volt line.

Wooden Transmission Poles.—The life of a wooden pole depends on the kind of wood, the character of the wood depending on where it was grown, where cut, heart or sap wood, seasoned or green, and the amount of combined air and moisture to which it is exposed. The

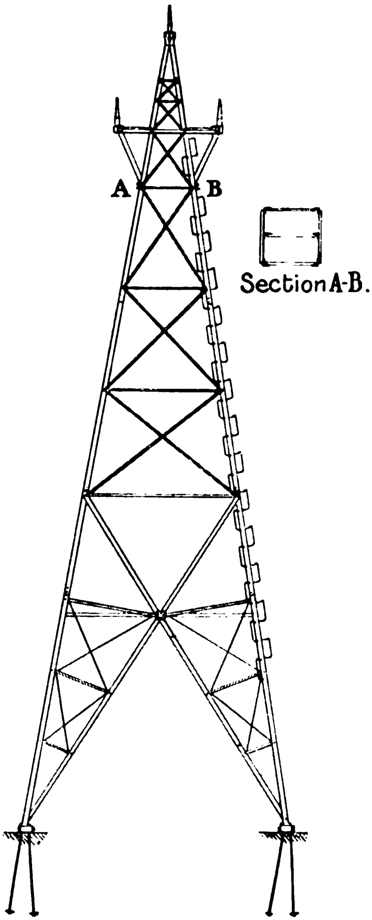


FIG. 13.

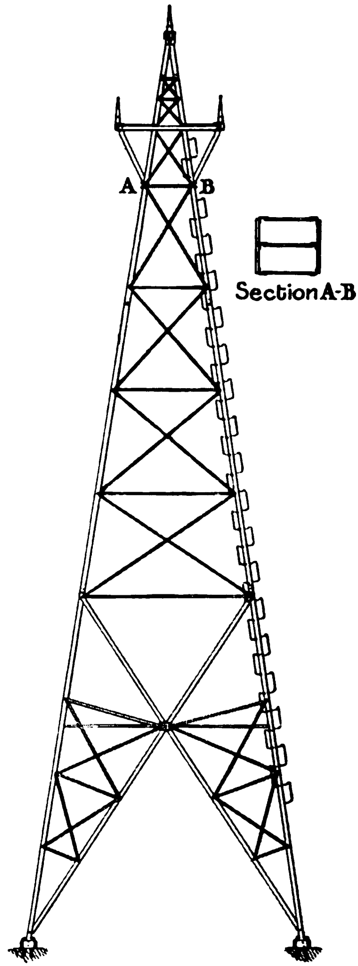


FIG. 14.

range of pole life for all different kinds and characters of wood now used for poles varies from 5 to 30 years, the average being about 12 years.

There are many processes in use for treating wood which must be constantly exposed to the ground and the weather, with the view of

preventing decay, such as contracting the sap and forcing into the wood cells a perservative compound, or by neutralising the sap with other compounds. Tarring, painting, or sealing the surface of green timber in any way is worse than useless, as the fermentative juices are confined within, and would shortly reduce the wood to a mere shell.

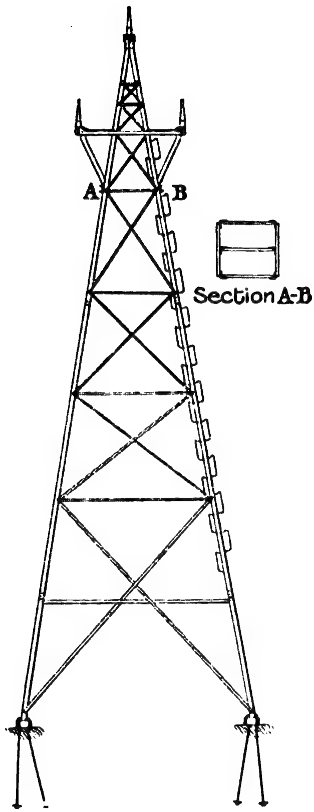


FIG. 15.

Poles from 35 to 60 ft. in length are extensively used for voltages ranging from 30,000 to 60,000, the lengths being increased to meet conditions over crossings, etc. No matter what the length of pole may be, the lowest conductor should never be less than 22 ft. from the ground. Poles above 40 ft. may be sawn off at the ground-line upon decay, and let down into the ground about 5 ft., depending on the condition of the surrounding country. Each pole should be numbered from a certain definite terminal or junction, and the number should be

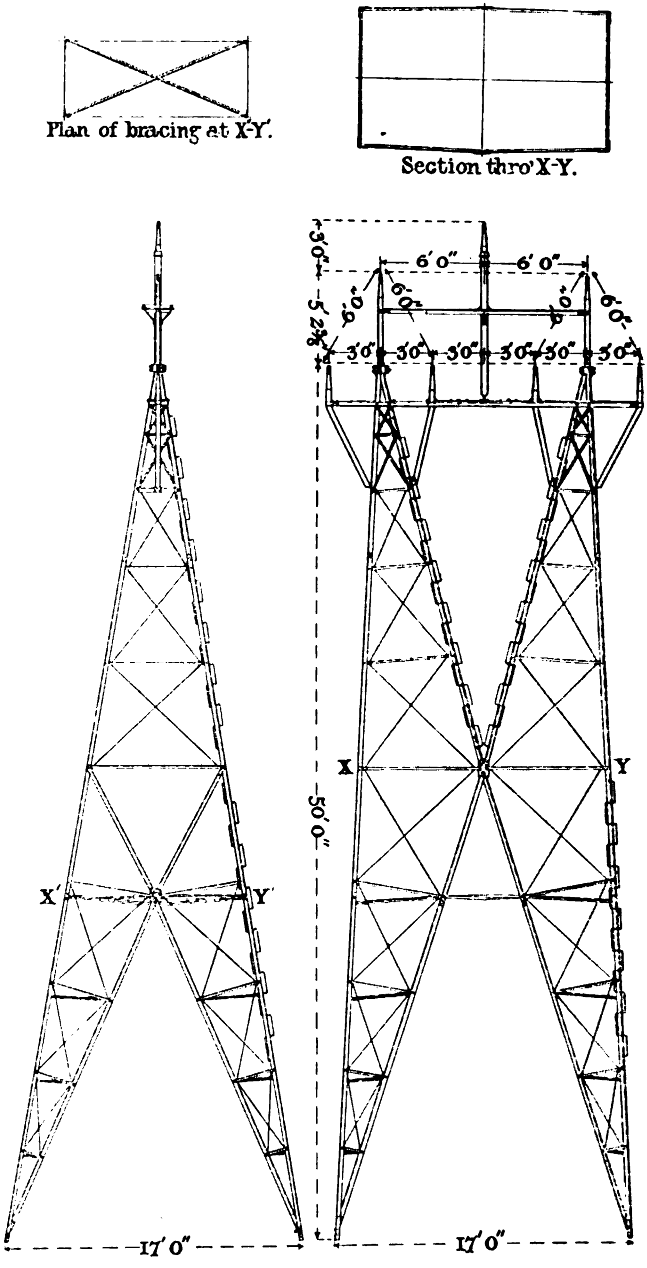

Plan of bracing at X'-Y'.
Section thro' X-Y.
3'0"
6'0"
6'0"
5'2⅞"
3'0"
X
Y
50'0"
X'
Y'
17'0"
17'0"

FIG. 16.

painted clearly on the pole at a distance of about 6 ft. from the ground-line. In this way a record may be made of the life, location, and resetting of every pole on the line.

Pole-tops are cut wedge shape at an angle of about 45°, and are

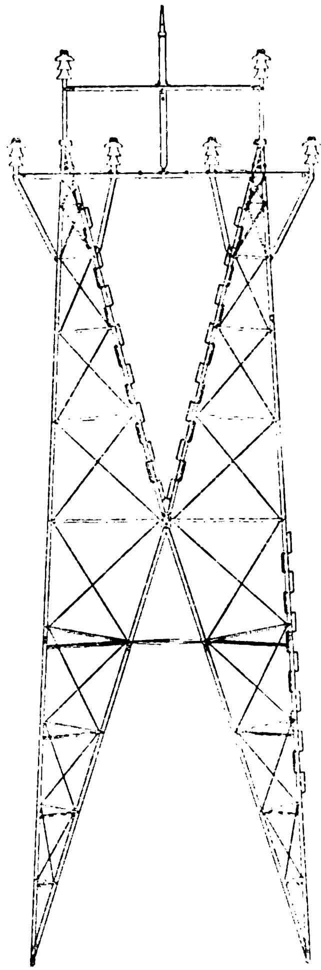


FIG. 17.

sometimes trimmed to a conical shape. Protection by nailing a sheet of iron plate over the top of each pole is of questionable value. In general it is considered preferable to apply a liberal coating of white lead and linseed oil, or mineral paint.

Line Insulators.—As the result of experiments and testing it is known that size alone will not produce efficiency in an insulator, but that the amount of surface as compared with the weight of the mass, bears a definite relation to its efficiency.

Insulators should be so designed as to withstand extreme weather conditions. Climatic conditions vary so much that an insulator which gave entire satisfaction in one place might be inadequate for similar work in another place. For high voltages, insulators are usually made in several pieces, held together by cement or glazed together while being fired in the kiln. Portland cement, litharge, and glycerine are commonly used for cementing the parts together. The principal points to be considered in the design of the pin-type insulator are:—

(*a*) Surface leakage resistance.
(*b*) Resistance to piercing.
(*c*) Striking distance between the conductor and the nearest point of support.
(*d*) Mechanical strength.
(*e*) Cost of Insulator.

(*a*) In order to decrease the surface leakage resistance it is necessary to increase the number of insulator parts.

(*b*) As the thickness of the insulator is increased it becomes more difficult to obtain vitrified ware without small cracks or flaws in the interior. Therefore the voltage is limited for a single piece of porcelain. It is customary to use pieces in series for high voltages, which have a high resistance to piercing.

(*c*) The striking distance may be increased by lengthening the pin, and by increasing the outside diameter of the outer petticoats. It is quite evident that the pin-type insulator for 60,000 volts is at its limit, because a further lengthening of the pin will produce a weak leverage and support, the weight and cost of the insulator is increased, and the striking distance rises rapidly with further increase in voltage.

(*d*) The multi-part pin-type insulator is generally the one that fails in the requirement of mechanical strength, for when a strain is applied to the insulator the parts are liable to become loose and broken.

(*e*) Porcelain is more expensive than glass, though it is more extensively used. The price of porcelain includes both the actual cost of the manufacture of the pieces used, and such pieces as are rejected on account of mechanical imperfections or failing to withstand the electrical test.

The object is to get an insulator which has a high resistance to piercing, a large striking distance between insulator and pin and insulator and cross-arm, a large surface resistance, and at the same time light in weight, easily tested, and cheap.

The glaze of insulators may be almost of any colour. The most common are white, brown, and slate. The most conspicuous of the three is the white, and the one least noticeable is the slate, especially where galvanised steel towers are employed.

A convenient method of testing line insulators is to place the insulator in a trough so that the water in which it stands forms one terminal of the insulator. The insulator being inverted, with the head immersed in water so as to cover the side wire-groove and the hole for the pin filled with water to serve as the other terminal. Insulators of special design often require special tests, which are given in such a manner as to bring about the severest conditions met with in practice.

A spray of water is allowed to play upon the insulator at a given angle. The spray being adjusted for a given rate per minute, at a given pressure, and from a given distance from the insulator. When the voltage has been raised sufficiently high to cause a flash-over of the insulator parts, it is considered as the determination of the capacity of the insulator for any condition of the atmosphere other than an actual cloud burst. Insulation tests of this character are very convincing, since both actual time and extreme atmospheric conditions are demonstrated. By neglecting time and temperature it is possible to obtain results varying by as much as 50 per cent.

Pins.—The wooden pin has an advantage in that it provides a certain amount of insulation, and the electrostatic field with the resultant brush discharge is much less pronounced than with a metal pin. It is, however, subject to injury by brush discharge at the pin, and when this occurs, or an insulator breaks down, the pin is destroyed, thus allowing the conductor to fall on the cross-arm, which will also be destroyed if of wood.

The metal pin has the advantage of greater mechanical strength, and holds the insulator and conductor in position even though the insulator may be broken down electrically. On this account the metal pin is considered preferable for use with insulators which have an ample margin of safety for service conditions. Where long spans are employed metal pins are necessary in order to obtain the required mechanical strength and safety.

Suspension-type Insulators.—One of the most important improvements in recent years has been the development of the so-called suspension-type insulator for transmission lines. This type of insulator is usually installed from four to eight in series, depending on whether the voltage is 60,000 or 110,000 volts. They are hung directly from the cross-arms, are free to swing, and to allow for adjustment of conductors which are dead-ended at the strain insulators. The latter are about 1 mile apart, and at all angles on anchor towers.

For high-voltage transmission lines the suspension-type insulator supersedes the pin-type insulator, and at the present time is considered standard for lines operating at voltages above 60,000. Unfortunately it requires a higher tower, which is a disadvantage, but the extra cost involved is offset by using less material for cross-arms and the tops of towers.

As an example of low maintenance cost of a transmission line operating with suspension-type insulators, and a line operating with

the pin-type insulators, experience with the Guanajuato Power and Electric Company and the Michoacan Power Company (branch Companies of the Central Mexico Light and Power Company) show that there is a great saving in favour of the suspension-type insulator, as shown in Fig. 18. For twelve months' operation of the two transmission lines, one with 85 miles of line using the suspension-type insulators, and the other with 110 miles of line using the pin-type insulator, careful records show a saving in insulators alone of 90 per cent. in favour of the suspension-type insulator, or 10 per cent. of the maintenance cost of the line equipped with the pin-type insulator.

The method of construction of the suspension-type transmission is to place at regular intervals along the line, about a mile apart, extra

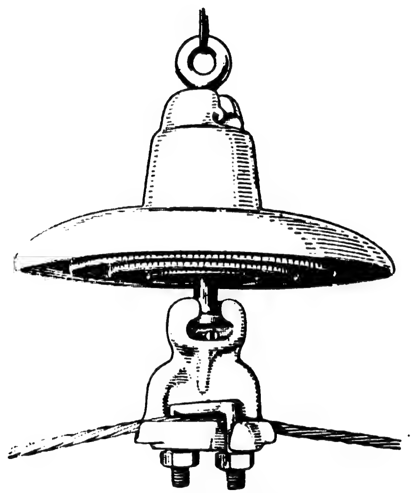


FIG. 18.—Showing Single Section and Clamp.

strong towers where dead-end insulators can be installed, from which the conductors are drawn up and dead-ended. Between the dead-end towers the conductors are hung loosely from each insulator—that is, loose enough to slip through in case of breakage.

Each part of this type of insulator must be designed to have a minimum electrostatic capacity. Tests at high voltage show that the larger the electrostatic capacity of insulating parts in series the greater the liability of puncturing the end part (not middle units) when a surge occurs on the line. When a number of pieces of porcelain are used in series the voltage drop over any one piece with reference to any other in the series will be in inverse ratio to the electrostatic capacity—that is to say, if one piece has twice the electrostatic capacity of another piece, and a voltage of 110,000 is applied to the two in

series, the first will take 36,666 volts and the second 73,333 volts, as it has but one-half the electrostatic capacity.

A flat plain disc has a greater electrostatic capacity than a similar disc with concentric petticoats on the under surface, hence a greater charging current and a lower effective resistance. Instead of making the disc perfectly flat it has been found better to curve it downwards for two reasons: first, to assist in protecting the lower surface from rainfall, which is necessary to maintain the effective resistance; and secondly, to increase its ability to withstand a mechanical blow, a curved disc being much stronger than a flat disc. The nearer the porcelain disc of a one-piece insulator approaches a flat disc at right angles to the axis of the insulator the greater will be its theoretical arcing efficiency, but this depends on the effective insulating value of the porcelain. To secure the latter the lower surface must have extremely high resistance.

Corona also reduce the effective resistance and increase the line loss. An insulator covered with corona acts as an effective condenser or conducting area, and therefore increases the electrostatic capacity. With properly designed petticoats the corona effect is reduced. The static discharge over the surface of the insulator is reduced with an increase in the surface resistance.

The design of insulator used on the Central Mexico Light and Power Company's lines is of the suspension type, and bears many points of considerable interest both as regards its mechanical and electrical qualities. In designing this insulator the aim has been to get maximum arcing length efficiency—that is, the ratio of the voltage at which the insulator flashes over to the breakdown voltage of an air-gap equivalent in length to the insulator. A 3-piece insulator of this type, as shown in Fig. 19, connected in series, has a dry flash-over of 220,000 volts, and a wet flash-over of 130,000 volts. The flash-over values of this insulator show about 12,750 volts per inch length of insulator under dry conditions, and about 7,600 volts per inch length of insulator under standard precipitation. Each piece or unit of the insulator has a dry flash-over of about 90,000 volts when used individually, but as the distance between units is less than the equivalent air-gap for the flash-over of 1 unit, the flash-over of the complete insulator is less than the sum of each unit taken separately.

Before assembling the porcelain with the metal part each unit is tested at the factory to a flash-over of approximately 85,000; after assembling the porcelain and metal part of each unit it is given a flash-over test (surge). The table given on page 538 shows tests made on this type of insulator. The values given will vary somewhat from actual operating conditions as the altitude, surface of the insulator, etc., are important factors limiting these values. However, the values given are a fair average of those secured on a series of many tests, and under favourable conditions better results can be obtained.

A 3-piece insulator of this type is considered quite ample for a line operating at 60,000 volts, and a 6-unit insulator for 104,000 volts. The

exact number of pieces per insulator will depend on the climatic conditions in the locality where the insulator is to be used.

The method of connecting each piece together is by means of a ball and socket joint, the ball being locked into place by inserting a cotter-key into the socket just to meet the ball pin. The ends of the cotter are spread so as to prevent its being taken from the cap casting, and it is so shaped that once pushed in place it cannot work from under the ball pin. This method of connection makes a convenient and flexible joint, permitting a rotary movement of each unit with respect to the other, and a flexible arrangement of the lowest unit which supports the conductor. In this manner each unit is free to turn with any swinging of the line conductors, which is very appreciable on long spans.

Flash-over Voltage of Insulator.

Number of Units.	Dry Test.	Standard Precipitation. Wet Test.
1	90,000 volts	56,000 volts
2	160,000 „	90,000 „
3	220,000 „	130,000 „
4	274,000 „	175,000 „
5	310,000 „	220,000 „
6	340,000 „	265,000 „

Line Protection.—Conditions are so varied on the different systems that it is practically impossible to specify a standard arrangement for the installation of arresters for each particular system. In view of this fact, it is thought that the following suggestions might cover points of most importance :—

In large generating stations, such as are being built at the present time in connection with long-distance lines, it is recommended that arresters be installed on the generator busbars, or low-tension side of the power transformers to protect them against internal surges.

On all outgoing and incoming transmission lines arresters should be placed on each line. They should be installed through a disconnecting switch preferably outside of the station, or as near as possible to the point of entry into the station.

Arresters or lightning rods should be installed at high places where the lines are exposed to lightning, such as the top of a mountain where no ground wire is used.

At least one ground wire should be installed along the top of the transmission line and grounded at every pole or tower.

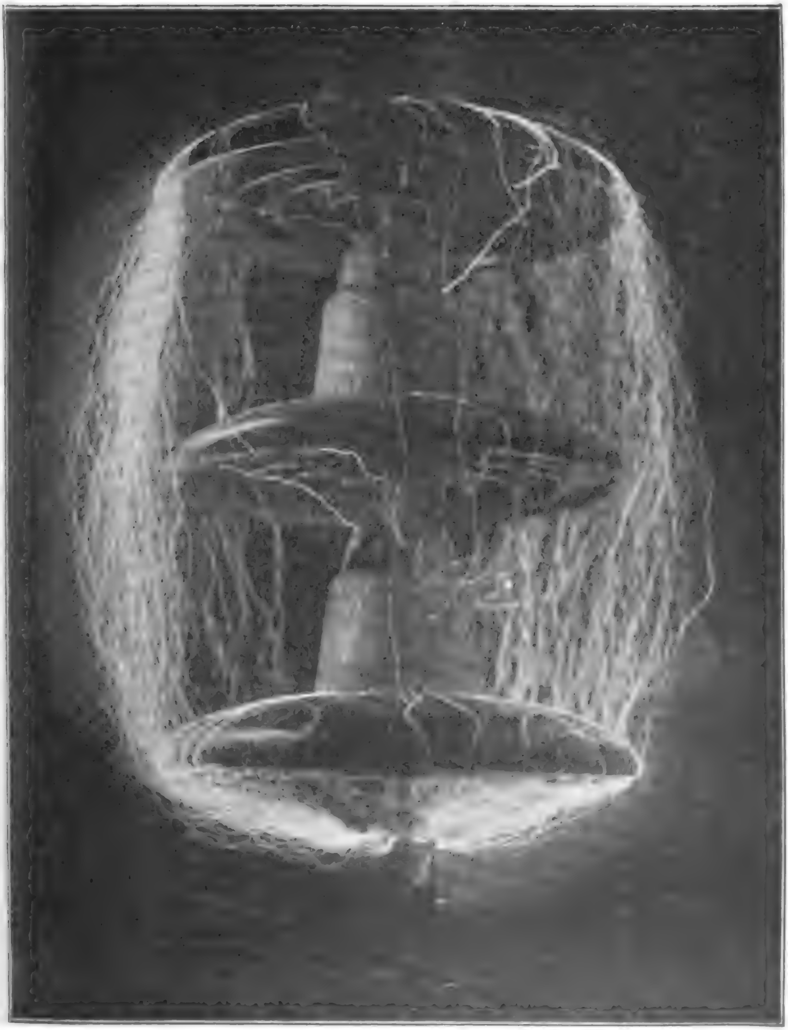


FIG. 19.—Flash-over at 220,000 Volts of a Three-part Insulator.

At the present time there are to be found very long lines operating at 110,000 volts without lightning arresters. According to all reports, no trouble has been occasioned from lightning. This is, of course, more the exception than the rule, and it is thought that the heavy corona loss on the long-distance transmission is much in favour of the good results obtained.

A method of protection giving the most promise for long-distance lines is the overhead grounded wire. At the present time quite a large number of long-distance transmission systems are receiving protection against lightning by the use of this method. Of course, the cost of a ground wire for the entire length of transmission is a serious matter, but under favourable conditions it is possible to erect transmission towers in which the ground wire strung along the tops of towers shall be an important factor of the mechanical stability of the line, and in the case of lines over 100 miles long it will probably save its cost by permitting a reduction in the weight of towers (intermediate) and dead-end towers, and their guys as the ground wire may be used to advantage in helping to guy its section on lines constructed with the suspension-type insulators.

The Grand Rapids-Miskegon Power Company protects its 110,000-volt line without an overhead ground wire, and apparently the method used is effective. An angle-iron extension 6 ft. above the topmost cross-arm is installed above the conductors which acts as a lightning rod, the angle-iron base extending 2 ft. below the cement foundations.

Another method for the protection of lines from lightning is being used on the transmission system of the Jhelum River Power Company, India. Two ground wires are strung above the top cross-arm, each pole structure being a double form of pole, the conductors being in the centre, and the ground wires on the outside and above the poles. A few years ago it was thought that this method of protection might be better than the use of a single centrally located ground wire, and with this in view it was finally decided upon. The line structure throughout is of the two-pole form, which extends for the most part over a very wild and mountainous country at an average altitude of 6,000 ft., and located at the foot of the Himalaya Mountains. At every alternate pole the ground wire is grounded, say, on the right to a 12 in. by 12 in. galvanised iron plate, and on the left one-pole structure in a similar manner. As far as the author is aware, no trouble of any kind from lightning has occurred, though during the months of May, June, and July the attack of lightning is very severe.

A single ground wire may do much to relieve the strain, but a much more certain arrangement will be obtained by using two grounded wires, one on each side of the line.

Lightning Arresters.—In the choice of lightning arresters for high voltages and long-distance lines, there seems to be little to select outside of the aluminium type, multi-gap type, and the water-jet. The type that has forced its way ahead and repeatedly demonstrated its value is the aluminium arrester.

One of the most important points to remember in the installation of lightning arresters is the ground connection. Various methods of making good grounds have been recommended, but the one that appears to give the least trouble is a number of iron pipes in parallel driven into the ground thoroughly moistened with water. A quantity of salt should be placed around each pipe at the surface of the ground. Each pipe should be connected to the iron framework of the station, metal flume, or water mains, or steel penstock; in fact, it is recommended to connect them to any good grounds around the station. The ground connections should be as short as possible, and from time to time the resistance of each ground connection should be measured to determine its condition.

Ground connections for arresters should be as short and straight as possible from the arrester to earth. A poor ground connection will render ineffective any provision for discharging the static electricity to earth. This question of ground connections is one which has been much discussed.

Electrical Calculations for Lines.—As a rule, transmission lines are designed by working out the energy loss, the regulation, the cost of conductors, and the cost of towers for a given set of assumptions as to the voltage and size of conductor, and then finding the effect of varying one or the other quantity to see if better results can be obtained.

A long line such as the Cook Falls, designed for an operating voltage of 135,000, according to calculations made, will have leakage and corona losses amounting to 1 k.w. per mile of line, and an apparent power approximating 11,000 k.v.a. for the first 125 miles. The 100,000-volt line of the Southern Power Company is estimated to have an ultimate charging current of 20,000 k.v.a. Very careful study of all conditions covering first cost, operation, and maintenance should be made before a final decision is arrived at as to the proper frequency, voltage, and size of conductor, etc., of any given line.

It has often been advocated that rotary condensers of ample capacity at the receiving stations of long transmission lines should be installed to take care of the power factor, and consequently reduce the kilowatt capacity of the step-down transformers, transmission line, step-up transformers, and generators. This may be all right in one or two cases, but for long-distance lines it barely seems necessary, since the inductive reactance is in the majority of cases neutralised by the capacity effect of long transmission.

For most practical purposes the total line capacity may be taken as divided into two equal parts, one of which is shunted across the line at the generating station, and the other at the receiving station respectively. Or, if a closer determination is necessary, the total line capacity may be obtained by dividing the capacity into six equal parts and shunting one part across each end of the line, and the four parts across the middle of the line. In the calculation given herein the former method of computing capacity effect will be considered.

Let us take a case of an average long-distance transmission system

giving average losses and regulation. Assuming a 200-mile 110,000-volt line with conductors weighing 2,710 lbs. per mile, the power loss when transmitting 20,000 k.w. over the total length of line will be 11·6 per cent. From such a case it is evident that with copper selling at 8d. per pound, the investment in copper would be £54,200, and assuming that power can be sold at the rate of £3 per kilowatt-year, the cost of lost power would be £6,960 per year.

In the following example the capacity on the line is shown to have an effect on the power factor which is much improved the nearer it gets to the generating station :—

Given—

$D =$	Length of transmission line in miles ...	200
$P_r =$	Power delivered in megawatts	20
$E_r =$	Voltage delivered in kilovolts	110
$\cos \phi_r =$	Power factor of delivered power	0·90
	Frequency of supply (cycles per second) ...	40
	Spacing of conductors (suspension insulator construction) in feet	10

Take from tables :—

	Size of conductor corresponding to 2,710 lbs. of copper stranded per mile	0·470 in. diameter
$r =$	Resistance per mile of copper in ohms	0·337
$x =$	Reactance per mile of copper ...	0·535
$t_r =$	Reactance factor ($\tan \phi_r \times \cos \phi_r$)	0·489
$b =$	Capacity susceptance per mile of two parallel conductors for a frequency of one cycle per second	$4·5 \times 10^{-8}$

$B =$ Total capacity susceptance

$$= f b D;$$

where f is the frequency, and D the length of transmission line in miles.

$e =$ Voltage between each conductor and neutral at receiver—

$$= \frac{E_r}{\sqrt{3}}.$$

$I_r =$ Current at receiving station—

$$= \frac{P_r}{\cos \phi_r \, E_r \sqrt{3}}.$$

* With the kind permission of Professor Harold Pender, Ph.D., the author is using formulæ which he considers the best and most practical for transmission engineers.

t_1 = Equivalent reactance factor of the first condenser at receiving station—

$$= t - \frac{4{\cdot}5 \times 10^{-8} (E_r)^2}{P_r}.$$

Equivalent power factor at the receiving station corresponding to t_1—

$$= \cos \phi_1.$$

R = Equivalent resistance per mile—

$$= \frac{\cos \phi_r (E_r)^2}{D\, P_r}.$$

t_2 = Reactance factor at receiving station—

$$= t + \frac{x}{R},$$

and power factor corresponding to t_2—

$$= \cos \phi_2.$$

p = Power loss on line—

$$= \frac{r}{R}.$$

P_g = Power in kilowatts at generating station—

$$= (1 + p)\, P_r.$$

k = Voltage drop on line—

$$= \cos \phi_2 \sqrt{(1+p)^2 + (t_2)^2} - 1.$$

E_g = Voltage at generating station—

$$= (1 + k)\, E_r.$$

Power factor at generating station—

$$\cos \phi_3 = \frac{1 + p}{1 + k} \cos \phi_2,$$

and reactance factor corresponding to $\cos \phi_3$—

$$= t_3 = \tan \phi_3.$$

t_g = Actual reactance factor of entire line (including the condenser at generating station)—

$$= t_3 - \frac{B (E_r)^2}{P_g}.$$

Actual power factor at generating station corresponding to the angle of $\tan \phi_g$—

$$= \cos \phi_g.$$

I_c = Charging current per mile per conductor—

$$= f b\, E_r\, 1{\cdot}155 \times 10^3.$$

Total charging current of line $= I_c D$.

Examples.—A load of 20,000 k.w. is to be delivered to a receiving station over a 3-phase 200-mile line, spacing of conductors 10 ft. (allowing sufficient clearance for suspension insulator construction), frequency 40 cycles per second, size of conductor 0·47 in. diameter copper stranded cable, voltage at receiving station to be 110,000, and power factor 0·90.

Find the voltage drop and power loss on the line, efficiency, voltage, and power factor at generating station, and the charging current of the entire line.

$$e = \frac{110}{\sqrt{3}} = 63{\cdot}5 \text{ k.v.}$$

$$I_r = \frac{20{,}000}{\sqrt{3} \times 110 \times 0{\cdot}9} = 166{\cdot}6 \text{ amperes.}$$

$$I_c = 40 \times 4{\cdot}5 \times 10^{-8} \times 110 \times 1{\cdot}155 \times 10^3 = 0{\cdot}2287 \text{ ampere}$$

and total charging current—

$$= 0{\cdot}2287 \times 200 = 45{\cdot}74 \text{ amperes.}$$

$$B = 40 \times 200 \times 4{\cdot}5 \times 10^{-8} = 3{\cdot}7 \times 10^{-4},$$

then—

$$t_1 = 0{\cdot}489 - \frac{3{\cdot}7 \times 10^{-4}(110)^2}{20} = 0{\cdot}266.$$

$\text{Cos}\,\phi_1 = 0{\cdot}966$—

$$R = \frac{0{\cdot}966 \times (110)^2}{200 \times 20} = 2{\cdot}922.$$

$$t_2 = 0{\cdot}266 \frac{0{\cdot}535}{2{\cdot}922} = 0{\cdot}446.$$

$\text{Cos}\,\phi_2 = 0{\cdot}914$—

$$p = \frac{0{\cdot}337}{2{\cdot}922} = 0{\cdot}116.$$

$$P_g = 1{\cdot}116 \times 20 = 22{\cdot}32 \text{ milowatts.}$$

$$k = 0{\cdot}914 \sqrt{(1{\cdot}116)^2 (0{\cdot}446)^2 - 1} = 0{\cdot}13.$$

Regulation = 13 per cent.

$$E_g = 1{\cdot}13 \times 110 = 124{\cdot}3 \text{ kilovolts.}$$

$$\text{Cos}\,\phi_3 = \frac{1{\cdot}116}{1{\cdot}130} \times 0{\cdot}914 = 0{\cdot}902.$$

$$\text{Tan}\,\phi_3 = t_3 = 0{\cdot}477.$$

$$t_g = 0{\cdot}477 - \frac{3{\cdot}7 \times 10^{-4}(124{\cdot}3)^2}{22{\cdot}32} = 0{\cdot}222.$$

$$\text{Cos}\,\phi_g = 0{\cdot}976.$$

GENERAL SUMMARY.

	Generating Station.	Receiving Station.
Voltage	124,300	110,000
Kilowatts	22,320	20,000
Power factor	0·976	0·900

Efficiency of transmission	= 88·3	per cent.
Percentage power loss on line ...	= 11·6	„
Percentage voltage drop on line ...	= 13·0	„

The annual interest, say, 5 per cent. on the investment of copper put into this line, will be £2,710.

Electrical Connections.—At the present time the electrical connections of transmission systems are about equally divided between the star connection with grounded neutral and the delta connection (non-grounded). One disadvantage that is usually spoken of when referring to the star-connected high-voltage system with grounded neutral is the short-circuiting of one phase when one of the conductors falls to the ground. It is generally acknowledged by the majority of transmission engineers that this condition is not a satisfactory one, but, when we carefully study the advantages and disadvantages of both the methods of connection (*i.e.*, delta-star to star-delta, and delta-delta to delta-delta, which are the two common high-voltage transmission connections in use at the present time), we find practically the same conditions are met with from the operating standpoint.

The star connection on the high-voltage side has the advantage of reducing the cost of insulators for the same line voltage, as the size of the insulator need be only 57 per cent. of that used on a line-connected delta.

The delta-connected system requires larger apparatus and larger insulators for the same line voltage, the advantage claimed for it being that, when one transformer of a group of three is cut-out (assuming delta-delta), the system is still operative.

It is very interesting to see the great strides that have been made recently in long-distance transmission high-voltage work, principally in connection with the design of high-voltage transformers of large kilowatt capacity, some of which have been installed at the places mentioned in Table I.

From the list of hydro-electric transmission systems (Table I., p. 36) it will be seen that the majority are operating with the delta connection. It shows the far-sightedness of transmission engineers in choosing apparatus designed to take care of future needs. For the want of this foresight many transmission systems are now operating at their limit—that is, with the star connection at every generating station and receiving station. For large units, such as are now being designed, it is important to use the delta connection on the high-voltage side, thus allowing for sufficient increase of power to keep the line loss and regu-

lation to a given value by a change from delta to star. Of course, as the load increases more apparatus will be added until it is deemed necessary to increase the line voltage, which in this case will not involve any extra strain on the line insulators.

During the early part of 1910 a change from delta to star connection was made by a very large transmission system operating in Mexico. To make the change according to the plans submitted, it was necessary to re-design something like 60,000-k.w. capacity of transformers originally designed for 60,000 volts (delta). The change from 60,000 volts delta connection to 85,000 volts star connection is undoubtedly a satisfactory one for the present load and the line insulators, the latter operating with less strain.

Operation.—The operation of long-distance transmission systems (in the majority of cases representing the consolidation of a number of

TABLE I.

System.	Kilowatt Capacity.	Voltage.	Connection.	Phase.
Mexican Light and Power Company, Ltd.	6,000	85,000	star	1
Stanislaus Power Company	3,750	138,500	star	1
	2,233	104,000	star	1
Great Western Power Company	10,000	110,000	delta	3
	5,000	90,000	delta	1
Great Northern Power Company	7,500	60,000	delta	3
Central Colorado Power Company	3,330	100,000	delta	1
Southern Power Company	3,000	100,000	delta	1
Hydro-electric Power Company	1,250	110,000	delta	1

local light and power and railway companies, and consisting of gas, steam, and water-driven plants each representing a fairly large undertaking) is a difficult proposition to manage, and is becoming more so as the transmission lines get longer and additional generating and receiving stations are put in parallel.

A system covering many hundreds of miles of transmission lines and many generating and receiving stations connected in parallel have what is now commonly called a "load dispatcher," or, as the author prefers to call him, a chief operating engineer. The chief operating engineer is usually located near the centre of distribution or at one of the largest receiving stations. He is in constant touch with the construction of and additions to any part of the system. He advises the shutting-down or starting-up of generators, switching in or out of groups of transformers, closing or opening of switches on line sections, and

control of all interruptions of service at the generating stations, the transmission lines, and the receiving stations with their auxiliary plants.

One of the best known methods of keeping in touch with the station and line operations and at the same time knowing the exact conditions of operation, is by means of a general plan showing diagrammatically the entire lay-out of the system. In this way orders are more easily understood and a check kept on them, since the chief operating engineer closes the identical switch or switches on his plan at the same time he gives an order for the operator to do so. A regular log-book is also kept which records the operation and interruptions of the entire system.

At each receiving station a local superintendent is placed in charge of the business of the corporation. The operation of this branch is in accordance with general sheets and forms issued from the head office, all local managers receiving similar copies. Apart from keeping to the forms and rules for operation, he is made subject to a check of all expenses and receipts at the commencement of every month or regular period during the month by the corporation's general accountant and head storekeeper who check up accounts, inventory, etc. Each local manager is a technically trained man with a broad experience.

On long lines it is now common practice to build patrol and emergency houses for the patrol men. The patrol houses may be located 10 to 20 miles apart, depending on the roughness of the country. The emergency houses may be only large enough to contain material such as insulators, line conductors, and guy wire, tools, etc., for an ordinary breakdown; they are usually located midway between two patrol houses.

At each, or at every other patrol house, it is advisable to provide a set of sectionalising switches which may be installed directly on the line structures or placed in a wing of the patrol house. If the line is of double-circuit construction, cross-over switches should be installed in addition to the sectionalising switches for changing from one line to another in case of trouble or necessary repairs.

Transmission lines may be patrolled once every day or one to three times a week, depending on their importance, location, condition, and length. In order to keep the men in shape, some line superintendents ride out to some point of the line and create a false alarm, taking note of the time it takes the linemen to get to the place where the alarm was made. When an alarm of this kind is reported, the supposed bad line is cut out between the two nearest sectionalising and cross-over switches, after which the men at both ends mount their horses and make for the point of trouble. This method of creating a false alarm has a tendency, if practised too frequently, to keep the men in doubt, although it gives them a better training should anything actually happen. The average lineman generally knows when something is wrong and when a false alarm has been reported.

For all long-distance systems independent telephone pole-lines

between generating and receiving stations are recommended. An independent telephone system between the main generating station and the most important receiving stations is indispensable, especially so when the chief operating engineer is located at one of these stations.

At the present time many systems are operating two lines of communication to the most important stations, one on the main towers and the other on an independent pole-line which is constructed parallel to and not far distant from the main transmission so that inspection and patrol of both lines can be made at the same time.

Telephone circuits strung below the main transmission line conductors are subject to a constant source of trouble and danger no matter how well the power transmission and telephone circuits are transposed, since an unbalancing of the power lines, or a ground on any one of the lines, will induce a voltage in the telephone circuits below, which is dangerous to any one using the telephone. In this the linemen are subject to great danger because no indication is previously given them before connecting their portable instruments to the line. Where telephones are used in patrol houses and in the intermediate emergency houses all danger in this respect is reduced to a minimum. On all long lines with a telephone service on the main transmission towers telephone transformers should be used.

When the telephones are not protected by means of a telephone transformer outfit, it has been found advantageous to provide a cross-over switch which is connected between an extension bell and the telephone, the former being kept on the line at all times when the telephone is not in use.

Power transmission companies invariably transpose their telephone circuits when carried on the same towers that carry the power transmission conductors, at every fifth or tenth tower. Some companies have used transpositions at every tower by means of a special insulator called a transposition insulator. This practice is not a good one, for the reason that too many short circuits occur where the two wires cross at the tower or pole, and in order to construct a line of this kind the wires must be cut at every tower or pole, resulting in imperfect joints and poor communication. Where telephone circuits are arranged on independent poles it is usual to transpose the wires at every tenth pole, or five transpositions per mile of circuit.

The present practice of transmission engineers is not to transpose circuits. Many companies do not think it worth their while going to the extra expense, some do not transpose at all, and others have but one or two complete transpositions for lines extending over 100 miles.

At the present time there are practically no data at hand showing results of operating telephone circuits on the same tower transmission lines built for and operating at 110,000 volts. For a short distance the Central Mexico Light and Power Company operate their telephone circuit to San Luis Potosi on the same towers supporting the power conductors, the telephone line complete from Zamora generating station to this point being just short of 200 miles.

Two factors limiting the distance to which power can be economically transmitted are the cost of delivering energy to the receiving station and the price which can be obtained at the receiving station distributors. The total sum of these factors may cover the cost of dams, pipe-lines, tunnels, generating station complete, transmission lines, sub-stations complete, and operating and maintenance costs, allowing for interest and depreciation on the investment.

Table II. is representative of a system in operation at the present time.

TABLE II.

Statement of General Expenditure on Various Parts of System.

System.	Capital Amount.	Interest. Per Cent.	Interest. Amount.	Depreciation. Per Cent.	Depreciation. Amount.	Operation Amount.	Total Amount.
	£		£		£	£	£
Dams	900,000	5	45,000	3	27,000		72,000
Pipe-lines and tunnels ...	750,000	5	37,500	5	37,500	15,000	75,000
Power station equipment ...	370,000	5	18,500	5	18,500		52,000
Power station building ...	200,000	5	10,000	3	6,000		16,000
Transmission lines	560,000	5	28,000	5	28,000	12,000	68,000
Sub-station building ...	74,000	5	3,700	5	3,700	12,000	7,400
Sub-station equipment ...	120,000	5	6,000	5	6,000		24,000
Total sum	2,974,000		148,700		126,700	39,000	314,400

This general statement is based on actual figures taken from construction and operation costs, and a conservative allowance for depreciation and interest.

The capital cost of the entire hydraulic and electrical parts of a transmission scheme such as outlined above are the determining factors whether a given water-power can be economically applied. Of course, all operating charges from the head works to the receiving station must be included.

Table III. represents the efficiencies of and losses on various parts of the same system shown in Table II.

The three tabulated statements shown in Tables II., III., and IV., are representative of a large hydro-electric long-distance transmission system.

Quite a large number of electric power companies have consolidated into one system. This is very marked in countries where water-power is plentiful, as, for instance, the western states of America and Mexico. The result of some of these developments have made possible long-distance transmission and the paralleling of numerous steam, gas, and water-power plants scattered about within a radius of from 20 to 200

Table III.

Statement of General Losses and Efficiency.

Parts of System.	a.	b.	c.	d.	e.	f.	g.
Per cent. losses	1·54	2·500	23·50	2·500	2·00	5·050	2·000
Kilowatt-hour losses of each part	3·30	5·340	39·50	4·200	3·28	8·150	3·000
Efficiency of each unit ...	98·50	97·600	81·00	97·500	98·20	95·200	98·000
Total efficiency	—	96·200	77·80	75·800	74·50	71·000	69·500
Actual kilowatt - hours in millions	313·00	207·700	168·20	164·000	160·70	152·600	149·600
Resulting price per kilowatt-hour in pence	0·09	0·177	—	0·335	—	0·464	0·525

a = Dams.
b = Pipe-lines and tunnels.
c = Turbines and auxiliaries.
d = Generators.
e = Generating station transformers.
f = Transmission line.
g = Sub-station transformers.

Table IV.

Statement of Load Factor, Minimum Price of Energy, Weight of Copper, and Copper Losses.

A.	B.	C.	D.	E.	F.	G.	H.	I.	J.
								d.	£.
0·4	1,090	64·00	7·00	131·00	124·00	5·35	1·16	0·560	277,800
0·5	1,210	71·00	9·75	163·95	154·30	5·94	1·13	0·450	279,400
0·6	1,320	77·40	12·40	199·01	186·60	6·30	1·10	0·377	280,100
0·7	1,425	83·50	15·30	230·90	215·60	6·62	1·07	0·326	280,240
0·8	1,520	89·01	18·20	262·00	243·80	6·95	1·04	0·291	280,380
0·9	1,590	93·20	21·60	29[illegible]·00	273·40	7·32	1·02	0·261	280,500
1·0	1,670	98·00	25·00	328·00	303·00	7·62	1·00	0·231	2[illegible]0,600

A = Load factor.
B = Weight of copper in tons.
C = Cross-section in millimetres.
D = Millions of kilowatt-hours lost on the line.
E = Millions of kilowatt-hours leaving the generating station.
F = Millions of kilowatt-hours entering the receiving station.
G = Average losses per cent.
H = Form factor.
I = Price in pence per kilowatt-hours at the receiving station.
J = Price of energy at the receiving station.

miles an economical success in so far as being able to give any class of consumer cheaper power than it is possible for the individual plant to generate.

In the actual cost of hydro-electric power development there are so many variables for different systems as to make impossible anything like a standard cost per kilowatt-hour. One particular system may consist of a short transmission line and comparatively simple and cheap hydraulic development. Another may just have the opposite

TABLE V.

Hydro-electric Rates for Power Consumers.

(Fixed service charge of 4s. per month per kilowatt for minimum power required.)

Kilowatt-hours per Month.	Price per Kilowatt-hour in Pence.
100 or less	3·500
100 to 150	3·250
150 „ 200	3·000
200 „ 275	2·750
275 „ 350	2·500
350 „ 425	2·250
425 „ 500	2·000
500 „ 625	1·750
625 „ 750	1·500
750 „ 875	1·375
875 „ 1,000	1·250
1,000 „ 1,250	1·125
1,250 „ 1,500	1·000
1,500 „ 2,000	0·750
2,000 „ 3,000	0·600
3,000 „ 5,000	0·500
5,000 „ 10,000	0·400
10,000 „ 20,000	0·375
20,000 „ 40,000	0·350
40,000 „ 80,000	0·330
80,000	0·320

extremes made up of an expensive dam and diversion site, undesirable hill-side supporting flume and penstock, costly foundation and site for generating station and tail-race, and a very long transmission line passing through a rough and dangerous country.

Rates for electric power are therefore adjusted according to individual circumstances influenced principally by capital charges, interest, and depreciation, and operating costs. Thus a consolidated system operating many generating and receiving stations scattered in different directions will necessarily have different rates for power purposes.

The present electric power rates on practically all hydro-electric systems of any importance and magnitude are based on a fixed charge per horse-power per month plus a definite amount per kilowatt-hour as recorded on the meter. There are, of course, other rates in use applicable to the class and character of consumer, as, for instance, the minute peak-load rate for mining districts where electric hoisting is done.

Below are given a few notes and tables of rates in use to-day on some very large systems.

Take, for example, a motor rated at 80 H.P. running 10 hours per day, the motor taking 80 H.P. at times as a maximum, but averaging throughout the day about 60 H.P. For 25 working days per month it would consume 15,000 H.P.-hours, or 11,200 k.w.-hours. The charge per month according to the above table would be made up as follows :—

	£	s.	d.
Charge for service demand of 80 H.P. at 3s. per horse-power-month	12	0	0
Charge for power (10,000 kilowatt-hours) at 0·4d. per kilowatt-hour	16	13	4
Charge for power (1,200 kilowatt-hours) excess of 10,000 kilowatt-hours at 0·375d. per kilowatt-hour	1	17	6
Total charge per month	£30	10	10

or, equivalent to £4 11s. per horse-power per year.

Table VI.

Hydro-electric Rates for Power.

Fixed charges per month per horse-power :—

(Manufacturing purposes.)

Motors from 1 to 2 H.P. at 6s. per horse-power.
" " 3 " 5 " " 3s. "
" " 6 and larger " 2s. "

(Irrigation and domestic water supply.)

Motors from 1 to 2 H.P. at 4s. 0d. per horse-power.
" " 3 " 5 " " 3s. 0d. "
" " 6 " 15 " " 2s. 0d. "
" over 50 " " 1s. 6d. "

Table VII. is representative of a large hydro-electric system and shows the price of power at two receiving stations, (B) being over 180 miles from one of the generating stations.

The load factor of any system has, of course, an important bearing on the cost of supplying energy. It has been defined in several different ways, but its general significance is the same in all cases—

TABLE VII.

Kilowatt-hours.	Price per Kilowatt-hour (A).	Price per Kilowatt-hour (B).
	d.	d.
100 to 199	4·00	4·50
200 „ 299	3·50	4·00
400 „ 699	3·00	2·75
700 „ 999	2·50	2·62
1,000 „ 1,499	2·00	2·50
1,500 „ 1,999	1·75	2·25
2,000 and over	1·50	2·00

TABLE VIII.

(Fixed charge per horse-power per month is 4s.)

Horse-power.	Price per Kilowatt-hour, 1st 100 k.w.	Price per Kilowatt-hour, 2nd 100 k.w.	All Above at
	d.	d.	d.
5·0 to 7·5	2·000	1·500	1·250
7·5 „ 10·0	1·750	1·500	1·250
10·0 „ 20·0	1·500	1·370	1·200
20·0 „ 30·0	1·370	1·250	1·000
30·0 „ 40·0	1·267	1·125	0·875
40·0 „ 50·0	1·125	1·000	0·875
50·0 „ 100·0	1·000	0·750	0·625

namely, it is a measure of the ratio of the average consumption to the maximum, the average usually being taken as the total energy in kilowatt-hours divided by the time of operation. There are several ways of rating the maximum, which may be taken as the sum of

the full-load rating of all apparatus, or the actual maximum demand registered, or it may be determined by the maximum load sustained for a given time.

Figs. 20 to 25 are examples taken from actual practice, and may be

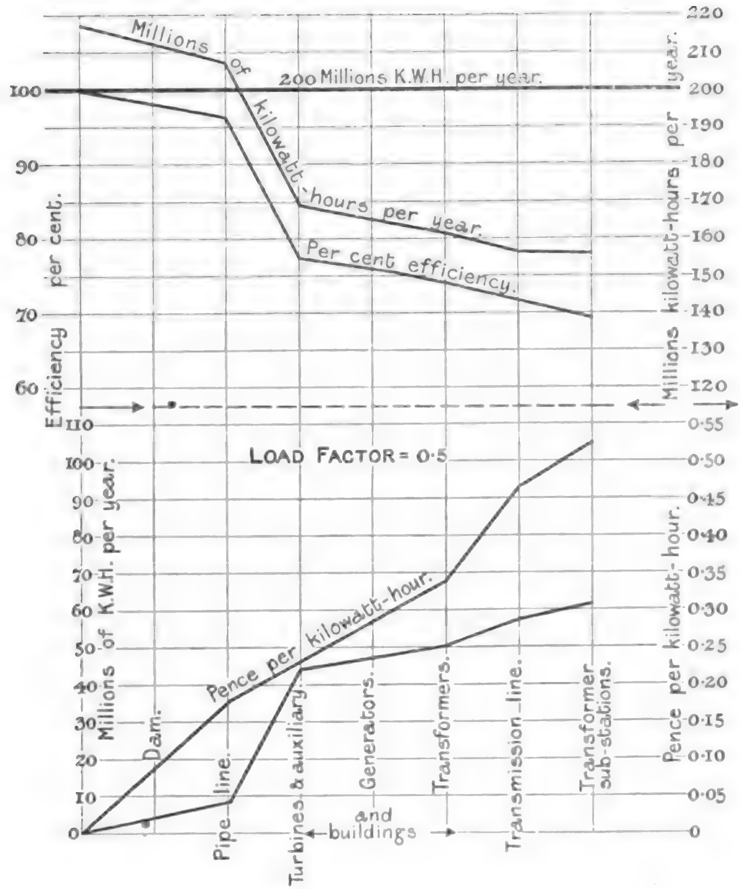


FIG. 20.—General Losses in an Hydro-Electric Transmission System.

useful to other companies about to adopt this method of charging for electric power.

In writing a paper dealing with long-distance transmission from an hydro-electric supply, it is only possible in this short space to mention a few facts and suggestions with the hope of gathering further ideas and practice that will add more interest and information for those directly engaged in this class of engineering.

No attempt has been made to cover anything but a few important points and practices of systems operating in different parts of the world, and as near as is possible taking an average of these different practices on systems of extreme importance and magnitude.

It is the author's opinion that in future years provision of reserve plant at various receiving stations will not be made. A properly

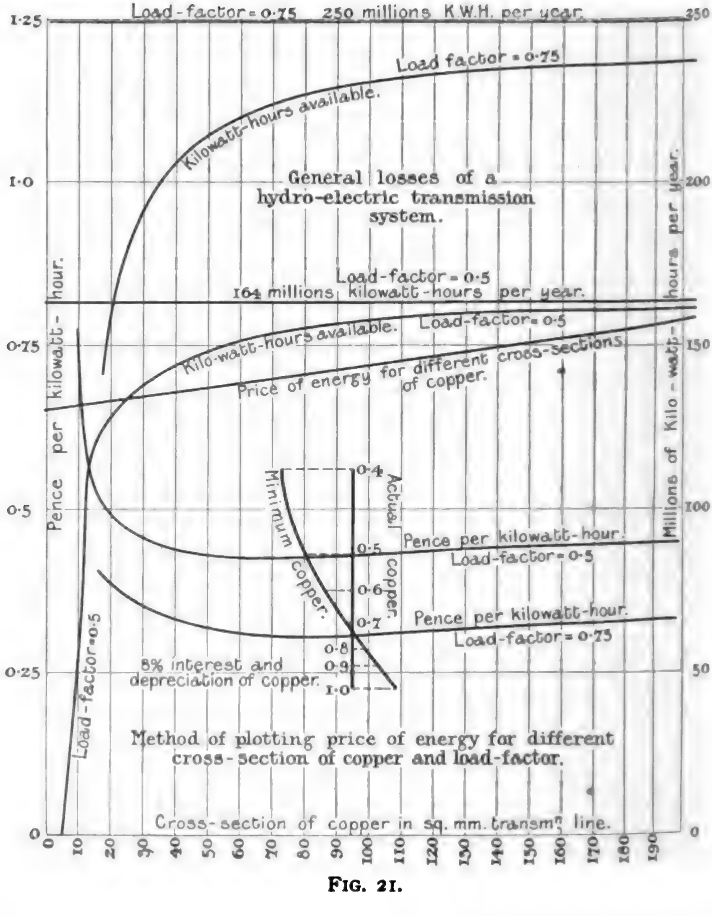


FIG. 21.

designed and constructive hydro-electric transmission system should not require any reserve steam or gas plants to take care of interruptions of service. In to-day's practice, for the majority of systems, it would be better to spend the money intended for reserve plant in additional machinery and apparatus at the generating stations, and an extra transmission line, or a better designed and constructed line from an electrical and mechanical point of view, and good, clear right-of-way.

Most engineers with much experience of flume operation and maintenance will agree with the author that this link of the system is a source of expense and worry, and the cause of many long interruptions, especially in those built of timber and above ground. When plants are fixed without flumes there should be no excuse for interrup-

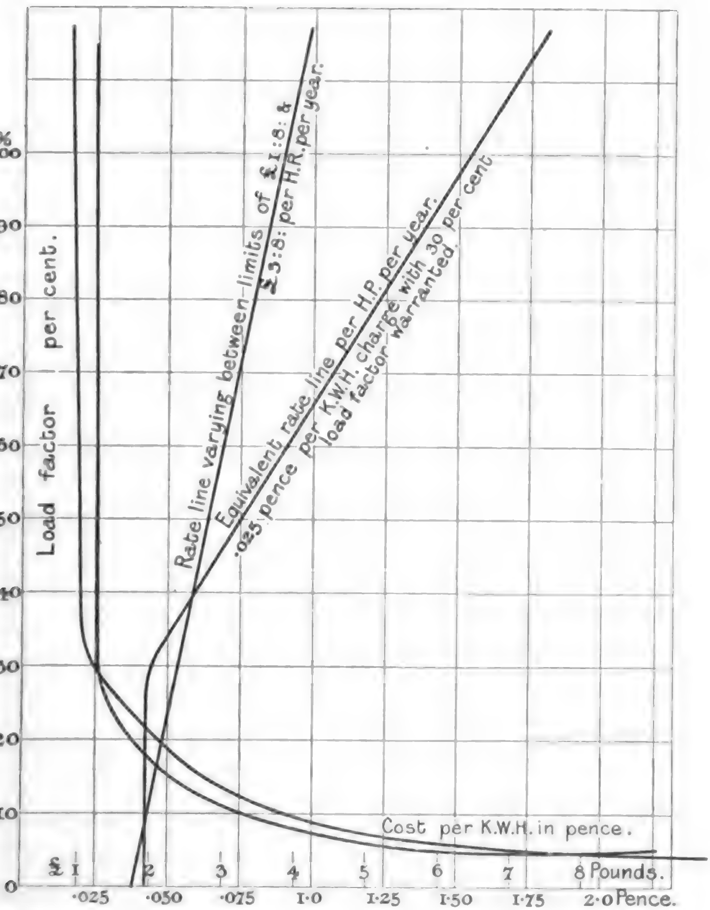


FIG. 22.—Method of Charging for Electric Power.

tions of service, even on systems operating hundreds of miles of line, other than the time it would take an experienced operator to start up an idle unit and manipulate the necessary switches in the generating stations and on the transmission line. This ought not to exceed two to seven minutes depending on the number of transmission lines, receiving stations, and the condition of telephone lines.

It should be the endeavour of the chief operating engineer to provide for all necessary switches, especially at points on the transmission line where patrol men are located and entrance to receiving stations so that quick transfer of lines can be made. If the installation of an extra switch at these points will save time only during an interruption it will pay the power company to satisfy this want even at the expense of building a structure and mounting an oil-switch designed for 120,000 volts. With three, four, or more transmission lines each

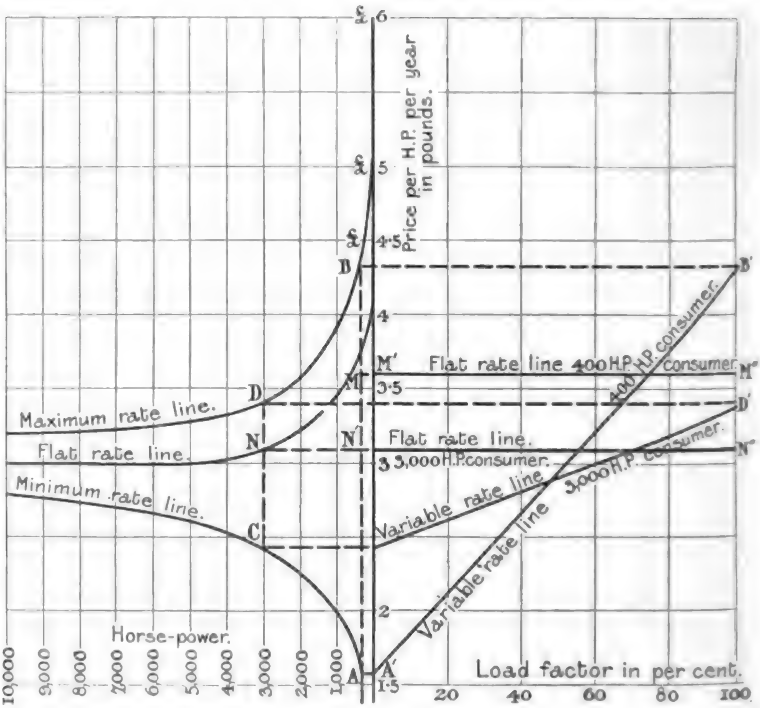


FIG. 23.—Results obtained under the Method in Fig. 20 of Charging for Electric Power.

designed for 10,000 k.w., it is important to have them inter-connected through cross-over switches for easy transfer should any line break down. A transfer of this kind may mean at least one tower structure per transfer of one line, the whole covering a space larger than an ordinary receiving station if all transferred at one point.

At the present time single-circuit transmission of electric energy has reached as high as from 25,000 to 50,000 k.w. per tower line.

A transmission tower line is now being built to carry two 3-phase circuits of 0·47 in. diameter copper conductors, one circuit on each

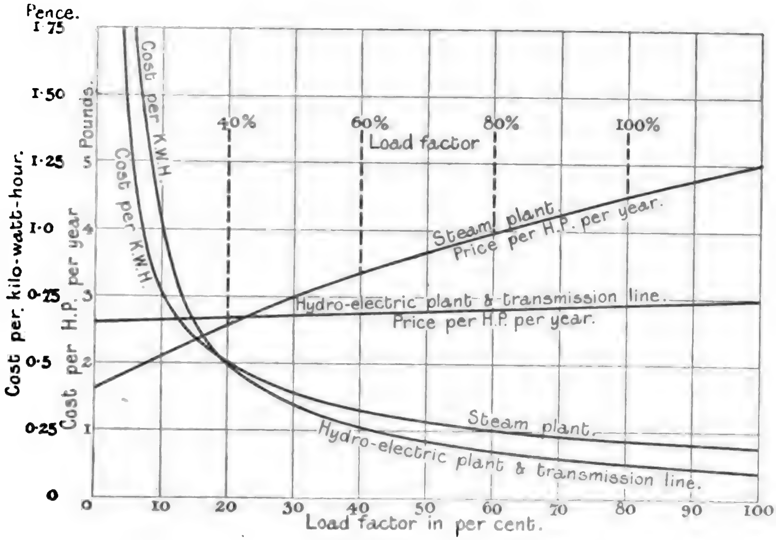


Fig. 24.—Method of plotting Costs per Horse-power per Year in Terms of Load Factor, Price per H.P.-year, and Price per Killowatt-hour.

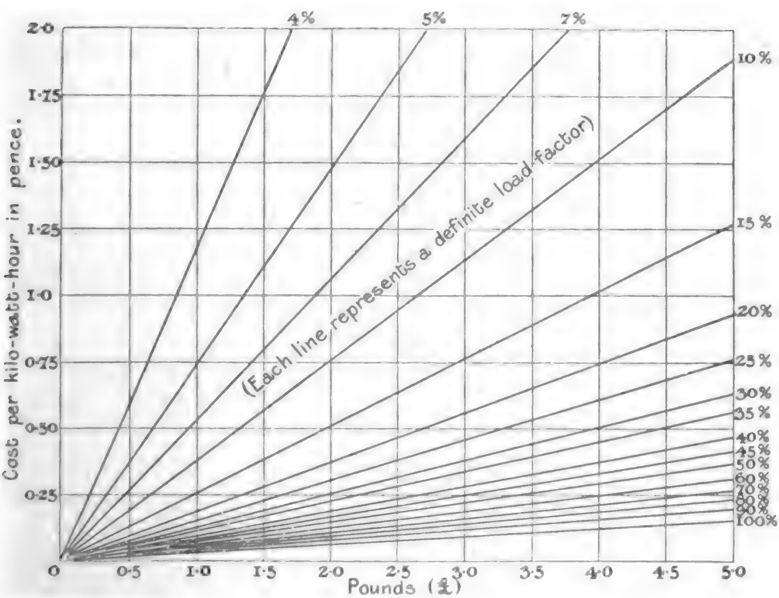


Fig. 25.—Method of Charging Cost per Horse-power per Year at Various Load Factors to Equivalent Cost per Kilowatt-hour.

side of the tower, and in a vertical plane suspended from the ends of the cross-arms, designed for 25,000 k.w. at 110,000 volts, or 50,000 k.w. for the three cross-arms, with ground wire connected to the apex of the tower. The spacing of the suspension towers will be about 600 ft. with strain towers about every mile.

It is difficult to realise fully the vast amount of responsibility that rests upon the chief operating engineer in charge of such a transmission system. No matter what ingenious scheme is adopted to provide for perfect switching, an interruption of a circuit carrying 25,000 k.w. will mean a comparatively long delay and probably a great loss of money. Take a case where the whole 25,000 k.w. is being transmitted to one receiving station over the one line to a distance of, say, 80 miles, it will probably take from 5 to 15 minutes to arrange the manipulation of necessary switches in the generating station, transmission line sections, and receiving stations, and will depend on their location. These switches in the case of the line would be fixed in the patrol houses or adjacent to them, and ready to be operated at a moment's notice, and those in the generating and receiving stations would probably be manipulated from the control-board. To order the closing and opening of switches and locate the faulty section is one of the simplest duties of the chief operating engineer. What really confronts him is a situation of a more serious character, which requires considerable thought, founded on long experience, thus preparing him to act quickly and with safety to life and property. Some of the most difficult problems that confront him are :—

(*a*) How to avoid a complete shut-down of the system when a load of this magnitude is interrupted by a short circuit and by a throwing-off suddenly of probably 50,000 k.w. as a result of the short circuit.

(*b*) How to get the entire system in regular operation again in the quickest time and at the least expense to the power company.

(*c*) How to regulate the voltage when 25,000 k.w. is added to one, or at the most two circuits, already fully loaded or operating at nearly their full capacity without taking off any consumer.

(*d*) How to regulate the load so that the power company and consumers get the minimum amount of loss. In this there may be probably 10,000 consumers affected, and the whole city left in darkness and tramway service stopped at the most important hours of the night.

On Table IX.* are given a few tests made on three different designs of towers (suspension, strain, and flexible), covering a set of specifications for a transmission line to carry 50,000 k.w. at 110,000 volts.

* By the kind permission of Milliken Brothers (Inc.) the designers and builders of these towers.

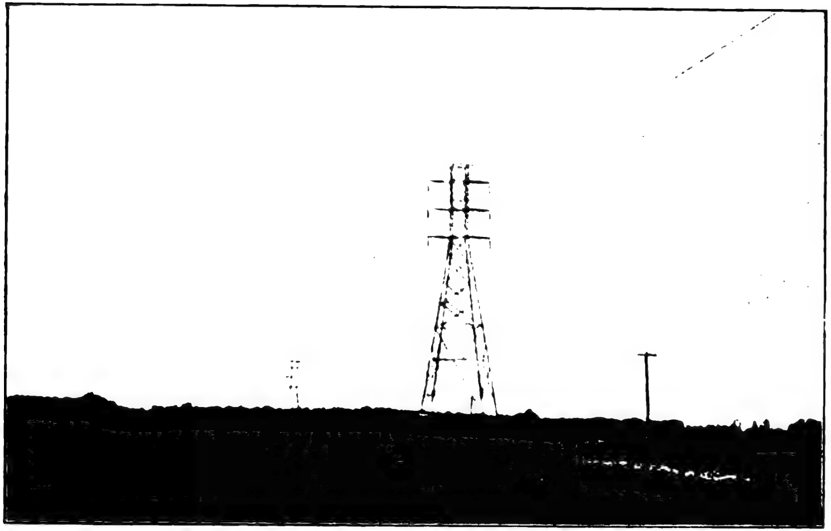


FIG. 26.—110,000-volt Transmission Line—Crossing a Cultivated Section of Land.

FIG. 27.—110,000-volt Line—Dead-end or Strain Tower.

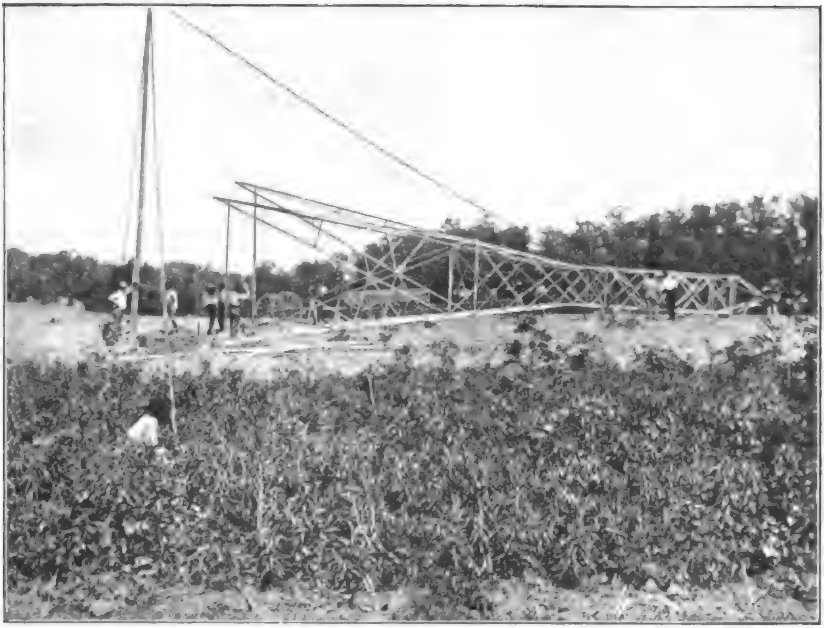


FIG. 28.—110,000-volt Line Construction—Ready for Tower Raising.

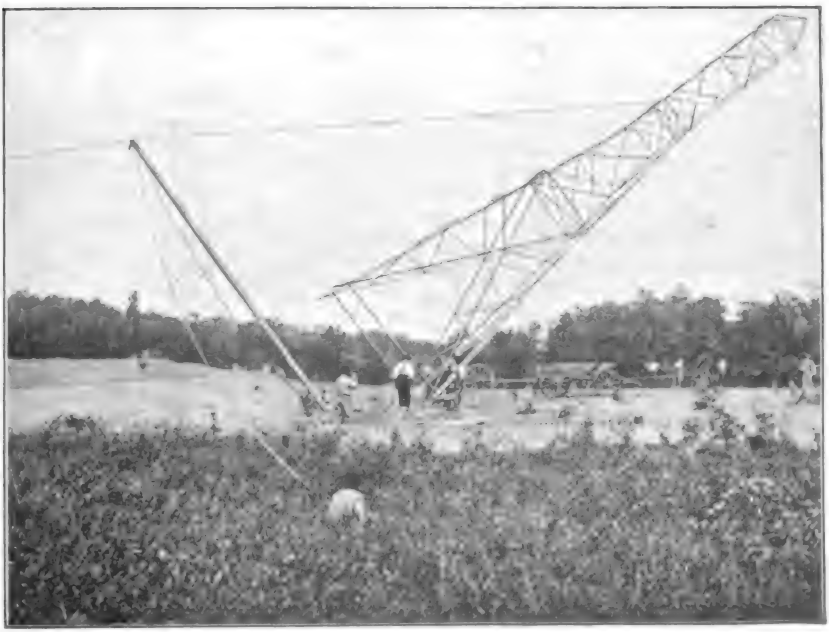


FIG. 29.—110,000-volt Line Construction—Method of Raising Towers.

TABLE IX.

Type of Towers.	Transverse Pull in Lbs.	Horizontal Pull in Lbs.	Vertical Pull in Lbs.	Aggregate Pull in Lbs.
Suspension Towers.				
Pull applied at the centre of gravity of the insulator supports	(*a*) 12,000	—	—	—
Pull applied at the end of each cross-arm in a direction parallel with the line	—	5,000	—	—
Load applied at the end of each cross-arm	—	—	1,500	—
Strain Towers.				
Pull applied at the centre of gravity of the insulator supports	(*b*) 30,000	—	—	—
Pull applied at the end of each cross-arm in a direction parallel with the line	—	5,000	—	15,000
Load applied at the end of each cross-arm	—	—	2,400	—
Flexible Towers.				
Pull applied at each of the three cross-arms	4,000	—	—	12,000
Load applied at the end of all cross-arms and *ground-wire* connections simultaneously ...	—	—	1,500	—

(*a*) and (*b*). On less restrictive sections the suspension and strain tower tests could be reduced to 10,000 and 15,000 lbs. respectively. These values correspond to those towers now used by the Southern Power Company.

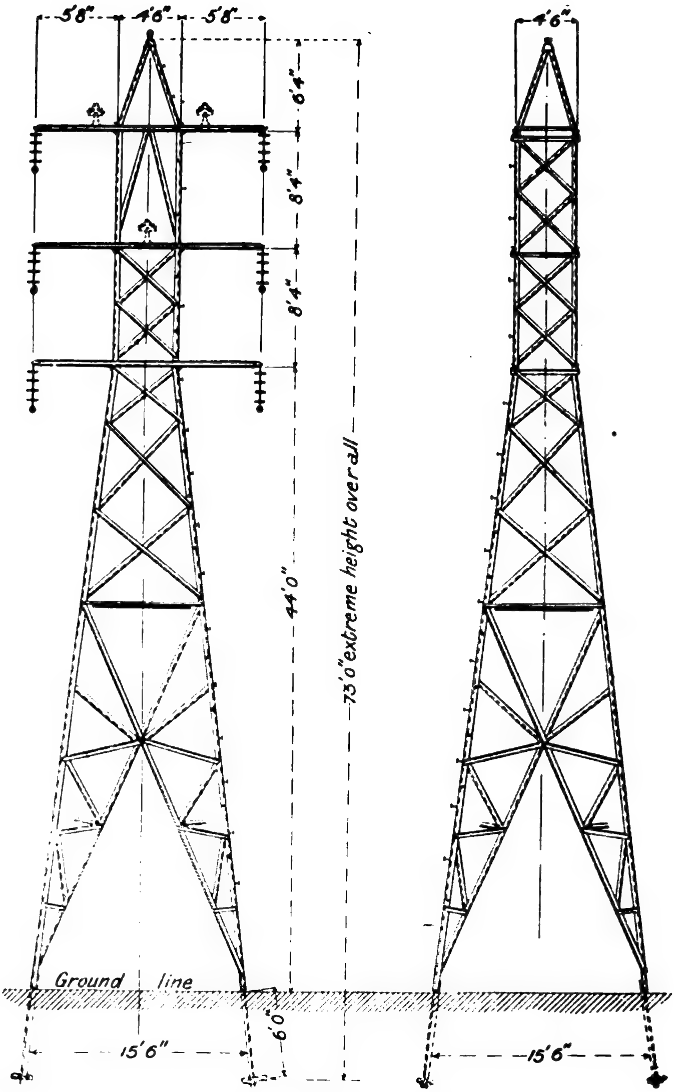


FIG. 30.—50,000-k.w. 110,000-volt Transmission Tower.

The approximate costs of towers designed to cover safely the above tests are :—

	£	
Suspension type...	26	per tower.
Strain type	35	"
Flexible type	20	"

Figs. 26 and 27 show a suspension tower and strain tower in the field in actual operation.

Figs. 28 and 29 show the same towers (not including the special 10-ft. extension at the base) in the field during the erection period.

This design of tower will permit a team of horses to pass underneath. The right-of-way man finds this a valuable feature to have when he is trying to get his right-of-way from landowners, as the actual space occupied by the tower amounts only to about 1 sq. ft. at each corner. It also enables a farmer to plant farm products inside of the tower with practically no loss of space.

Fig. 30 shows the outline and dimensions of the tower of the suspension type.

EXTRA-HIGH-PRESSURE TRANSMISSION LINES.

By R. BORLASE MATTHEWS and C. T. WILKINSON, Associate Members.

(*Paper received November* 30, 1910. *Read before* THE INSTITUTION *January* 26, 1911; *before the* NEWCASTLE LOCAL SECTION *January* 30, 1911; *before the* MANCHESTER LOCAL SECTION *January* 31, 1911; *and before the* YORKSHIRE LOCAL SECTION *February* 15, 1911.)

In accordance with the Board of Trade Regulations, the term 'extra-high pressure" is understood to refer to voltages of over 3,000. In this paper, however, it is proposed to deal with the construction of what might perhaps be termed "extra extra-high pressure lines." Lines operated at such voltages are not of immediate interest in connection with works carried out in this country, but the time is gradually drawing nearer when they will become of much more importance. Furthermore, a number of schemes involving these very high pressures are at present being engineered from this country. Progress in the direction of the development of high-pressure transmission systems must necessarily be slow in a conservative country like England, where the population is very dense, as compared with the sparsely inhabitated tracts of a big continent like America; nevertheless, the attitude of the authorities is gradually changing.

One of the first bare overhead lines erected outside private premises, to operate at 10,000 volts in the British Isles, was installed in the Isle of Man about eight years ago, one of the present authors being fortunate enough to be associated, at that time, with the contractors who carried out the work. Since then, lines operating at even higher pressures have been put up in England, among which special attention may be drawn to the 20,000-volt overhead lines of the North-East Coast Power Supply System. This necessity for the adoption of extra-high-pressure transmission lines is emphasised in the inaugural Presidential Address of Mr. S. Z. de Ferranti to this Institution. Such lines would be essential to the carrying out of the complete scheme outlined by him, if it were to be accomplished at a mininum capital cost, for underground cables would involve far too great an expenditure.

Limits of High-tension Transmission.—Several power supply undertakings are now operating successfully at 110,000 volts, a few 140,000-volt lines are projected, and a pressure of 200,000 volts is considered to be within the region of practicability; in fact, such a pressure is now regarded as much more practicable than was one of 100,000

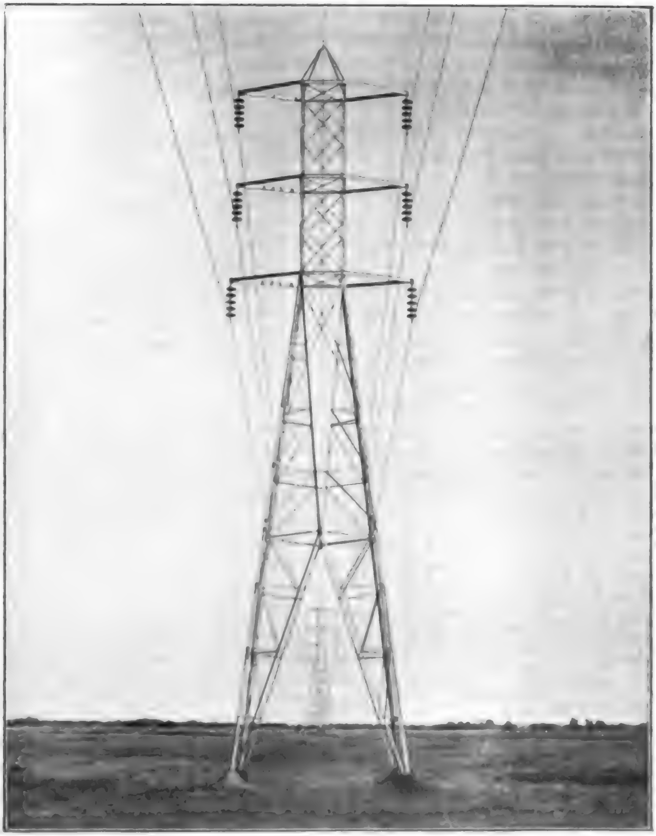


FIG. 1.—A Typical 110,000-volt Two-circuit Tower. (With Suspension Type Insulators.)

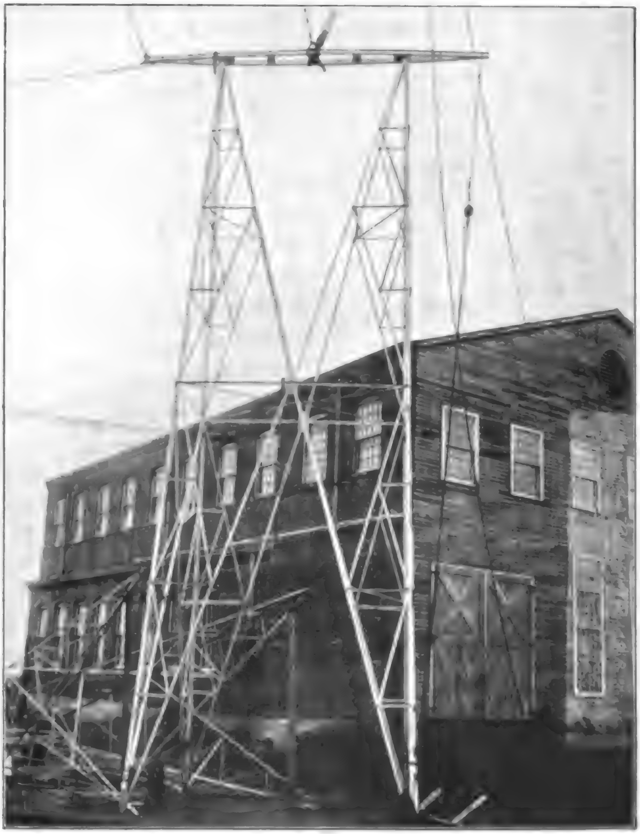


FIG. 2.—A Typical 100,000-volt Single-circuit Tower. (For Use with Suspension Type Insulators. The Earth Wires are attached to the Top of the Cross Arm.)

FIG. 3.—A Flexible Steel Tower Transmission Line.

FIG. 3A.—Side View of the Flexible Tower shown in Fig. 3.

volts a decade ago. Transformer manufacturers and insulator makers are considering the construction of apparatus for this abnormal pressure.

Such schemes as that proposed for transmitting power from the Rhone Valley to the City of Paris have led to very serious considerations of the problems involved. Transmission lines operated at over 100,000 volts have been in satisfactory operation for some two years, and transmission over distances up to about 240 miles has been safely accomplished. Niagara power is transmitted to Syracuse—150 miles away—at a pressure of 60,000 volts only. There seems no reason why these distances should not be largely exceeded, the question being almost entirely a financial one, since there are not many circumstances under which it would pay to build lines of greater length. The conditions, of course, under which this might be possible, are those in which the market is prepared to pay unusually high prices for the power, and where there is no possibility of competition from electric plants operated by steam or other prime movers. It must also be borne in mind that distances of transmission above those mentioned may become unnecessary, since it might be better to move the market nearer the power plant, or to build up a new market in the neighbourhood of the power plant. Both these methods have been already followed.

In other words, the day has now arrived when there is no engineering difficulty which will prevent the building of transmission lines of great length, but financial considerations may, from our present point of view, limit that length to about 400 miles.

Supporting Systems.—Wooden pole supports for such high-tension lines are now practically a thing of the past, for in addition to the difficulty encountered in providing cross-arms of sufficient length, it is found more economical to adopt wide spacing and high supports, and under these conditions steel structures are very much more satisfactory in every way, including prime cost. As regards the design of these structural steel towers, practice is settling around the types illustrated in Fig. 1 for two-circuit types, and Fig. 2 for single circuit types.

The above towers employ suspension type insulators, instead of the pin type petticoat insulators formerly employed. This is found to be the best practice for lines whose working pressure exceeds, or may in the future exceed the neighbourhood of 60,000 volts. The chief difference in towers constructed for the pin and the suspension types of insulator, is the slight increase in the height of the towers necessitated by the use of the latter type of insulator, which, however, is offset to a great extent by the reduced amount of metal required in the cross-arms, and the reduced torsion stresses which the tower must meet in case of the breakage of a wire. Another point which makes the suspension and pin types of tower practically the same with regard to weight is the fact that in any case the overhead ground wires (the use of which is now almost universal) must be supported, and a greater additional height above the insulators

must therefore be used for the pin type than for the suspension type in order to maintain the same shade angle. Further, the use of the larger size of pin insulator involves a very severe twisting stress on the cross-arms in case of wire breakage, and hence an ample and increased section has to be provided to allow for this contingency.

A careful study of the mechanical features of the transmission line as a whole led one of the authors some time ago to conceive and erect the first line of flexible steel structures in America, thus departing from the usual practice of rigid structures. An illustration of this line is given in Fig. 3. This system proving very successful and economical, he then became closely associated with the installation of several other transmission lines of this type.

From the mechanical point of view, the worst stresses, for which a transmission line must be designed, are those due to the breakage of wires accompanied by ice deposit and wind of high velocity blowing at right angles to the line. These stresses are all comparatively steady except those due to wire breakage, which are in the nature of severe mechanical shocks, and it was the idea of attempting to overcome this difficulty by absorption of the shock into the system as a whole, rather than by impact on rigid towers of the four-footed type, that led to the design of the flexible tower. After a few lines on this system had been erected, attention was drawn to the somewhat similar work due to Signor Semenza which had been independently experimented with in Italy, and it was found that in applying this type of structure to American practice some noticeable advance had been made over the work of previous investigators. The severe commercial criticism which all new projects meet with in the United States by those interested in them, led to great efforts towards economy, and that important element in final economy—durability, with the result that a very satisfactory system has now been evolved.

Though wire breakages are fortunately not a frequent occurrence, when they do take place the trouble may either be limited to the twisting or stripping off a few cross-arms, or it may extend to the wrecking of several towers. It was with great pleasure therefore that the authors found the flexible tower system to be succeeding admirably in practice, and that deliberate wire breakage under the worst weather conditions obtainable has shown this system to be far more reliable than that in which the four-footed rigid towers are employed. In such lines the flexible structures may be interrupted by a rigid tower at every tenth point, but experience shows that the far cheaper method of double guying every fifth flexible structure is more satisfactory for lines using the smaller sizes of cables.

In considering such a system, the amount of safe bending of the towers, their distance apart, the number of wires, amount of sag allowed, etc., must be borne in mind. Slight bending or deflection of the tower in the direction of the line results in the shortening of the span on one side. This leads to a difference in the stresses of the wires in the different spans, resulting in a tendency for the wires

themselves to act like mechanical springs, and absorb the majority of the shock which was produced by the breakage of the others. This re-distribution of stress causes the wire to assist in a remarkable degree in the support of the towers and prevents the development of serious distortion.

The main object in the design of these towers in this particular manner, is to provide ample strength sideways to withstand the wind stresses, and in the direction of the line, to make use of the strength of the wires themselves to assist the structures. How great is the strength available in the wires themselves may be realised when it is recalled that a line designed to carry six No. 1 B & S gauge (0·2983 in.) wires and one $\frac{3}{8}$ in. Siemens-Martin steel ground wire will, after the breakage of any two coppers, have a combined ultimate wire strength in the remaining wires of approximately 20,000 lbs. Independently, then, of the strength of these

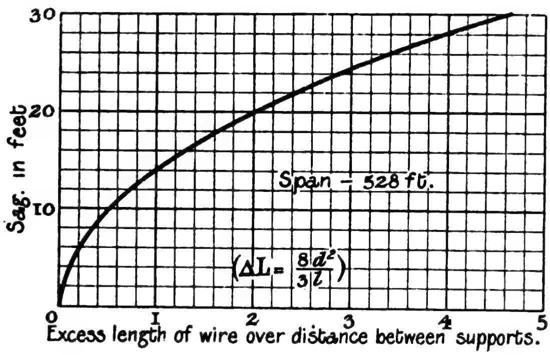


FIG. 4.—Sag of Wire between Supports.

intermediate structures themselves, and in addition to the strength which is necessary to enable them to withstand the shocks of rough transportation, quick and cheap erection, stringing, etc., they must be capable of bending sufficiently to enable the remaining wires to tighten up on one side and slack off on the other, in order to reach a condition of mechanical equilibrium.

Curve Fig. 4 is plotted between the sag of wires and the excess length of wire over the distance between supports, the study of this showing very clearly the deflection necessary for various lengths of span, sag, etc. For example, consider the case of a flexible tower assumed to have no strength in the direction of the line, and carrying seven wires attached on either side to rigid towers at a distance of 528 ft. from the central tower and set to a sag of 12 ft. If two wires be now cut, after the momentary surge has spent itself, the following conditions will obtain :—

Let T_1 = the total tension on one side of the tower ; T_2 = the total tension on the other side ; S = the original sag before breakage

(= 12 ft.) ; and S_1 and S_2 = sags after breakage. Now, $T_1 = T_2$; as an approximation it may be assumed that the sag in each wire is inversely proportional to the tension and hence $5\ S_2 = 7\ S_1$. Assuming a straight-line law over the working range, $S_1 + S_2 = 24$; and $S_1 + 1{\cdot}4\ S_1 = 24$. Hence $S_1 = 10$ ft. and $S_2 = 14$ ft.

Referring to curve Fig. 4 it is seen that for a 12-ft. sag the excess length of wire was 0·72 ft., and for a 14-ft. sag, it is 0·96 ft. ; therefore the increased length is 0·24 ft. = 2·9 in., or, allowing for stretch of the wires, say 4 in. Semenza and other investigators have shown that this deflection is one-half what would occur if the wires were supported by a long line of flexible structures of the requisite strength. Hence the deflection under actual conditions with the line built entirely of flexible structures will be 8 in. or less, depending on how frequently "dead-end" towers are used.

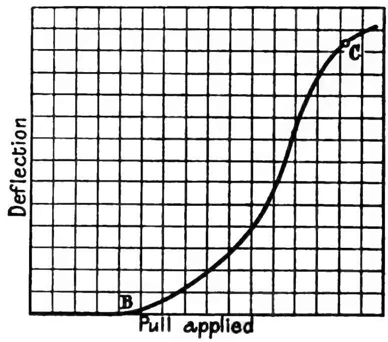


FIG. 5.—Yield of the Earth Foundation.

The above treatment of the whole subject is simple and approximate, but it has the advantage that it enables an easy grasp of the phenomena, and the still greater advantage that for practical conditions it gives all the accuracy which can possibly be desired. In addition to the deflection obtained by this method, allowance must be made for the surging which will occur at the moment of the wire breakage.

In addition to the above, a matter of great importance in the design of flexible towers is the behaviour of the earth. The amount and the manner of its yield when frozen hard to a depth of several feet, as occurs in the United States, is problematical; but with the weather conditions obtaining in England, the conditions may be assumed to be roughly the same both in winter and summer. The curve Fig. 5 shows the nature of this yield, which, happily, is such as to assist rather than hinder the operation of this flexible tower construction. It will be noted that for a slight pull—that is, until the value B pounds is reached—there is no measurable yield of the earth. From that point up to a pull of C pounds, however, the earth yields very readily,

and at C a critical point is reached, after which the earth packs up and very readily offers such resistance that the tower will break before any serious movement has occurred. The slight movement obtained at first is, however, in many cases, sufficient to give the tower designer a very free hand in considering the flexibility of the structure.

Steel Poles.—Several standard sheet and ferro-concrete poles now on the market are interesting in connection with the construction of lines of lower voltages, since they represent very fairly the characteristics of wood poles with regard to flexibility. These poles, if set at distances of from 300 to 350 ft. apart, depending upon the size and number of the wires to be carried, give a strength and price for line construction which is very favourable when compared with wood pole lines. They have the advantage over towers, in that it is frequently possible to obtain greatly reduced right-of-way charges. In the United States, land-owners may be generally persuaded to take the same price for rights-of-way as they would for wood poles, while for a steel tower, which occupies considerable ground space, many times the price for a wood pole is frequently asked.

Steel poles, however, have the disadvantage that it is somewhat difficult to obtain a good foundation at points where the line is subject to steady stresses in one direction—such, for instance, as angles in the line, and where guying is impracticable. Considerable care must be given to the foundations, and a cross-piece attached to the pole below the ground may be found necessary.

The Comparative Cost of Flexible Towers, Rigid Towers, and Wood Pole Lines.—The task of giving the costs for transmission lines is a very difficult one, since even among the one or two hundred lines that have come under the attention of the authors the conditions varied sufficiently in every case to make individual estimates necessary. If, however, a straight right-of-way is assumed with good local transportation facilities, soft soil, and level country, with normal weather conditions, the curves shown in Fig. 6 could be taken as fairly representative of the cost per mile for a given voltage. These costs are, of course, given independently of the conductor, but include the poles or towers with all the construction necessary for erecting them, the digging of the foundation holes, the placing of cross-arms, insulators, and their attachment, the stringing of the wires, a single ground wire of $\frac{3}{8}$ in. steel, and, in fact, everything complete and ready for the line to operate, less the cost of conductor.

It is not practicable to build a wood pole line for above about 40,000 volts for two circuits, since the length of the cross-arms becomes excessive. Further, it will be seen from Fig. 6 that the cost curve slopes up somewhat steeply, and in the neighbourhood of 50,000 volts would cross the flexible tower curve. Since the latter means a construction with an average life of thirty years, whereas the wood pole line can only be assumed to have an average life of twelve years, it is hardly possible that any one would wish to build a wood pole line for this voltage. The curves include the cost of all labour, erecting towers,

digging foundation holes, stringing wires, cost of insulators and mounting same, and all local freight (that is, from station or railway to the position of the line, and the cost of distributing the towers, etc., to their proper points).

While considering the question of costs, it may be of interest to look into the figures associated with the sub-station portion of the equipment at various voltages, and accordingly a curve (Fig. 7) is given of a 2,250-k.w. sub-station, which shows clearly how the cost

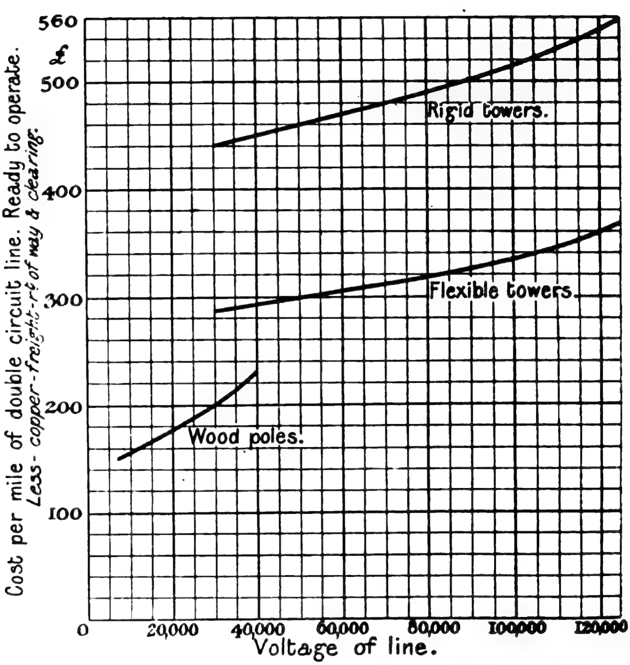


FIG 6.—The Comparative Costs of Wood Pole, Flexible and Rigid Tower Transmission Lines (less Cost of Conductor).

increases with an increase of voltage. Of course, it must be borne in mind that, while the costs of both the line and the sub-station equipments rise with the voltage, on the whole, due to the saving in expenditure on conductors and the reduction of transmission losses, the total economy of the very high-voltage system of transmission over a considerable distance is, of course, all in its favour.

While the costs given above with reference to line construction are based upon American practice, it is interesting to note that the total costs for the construction of similar lines in the South of France work out at almost identically the same figures. Of course, the individual

items that make up the total vary considerably. Such an item as labour, for instance, is very much cheaper in France than in America; but, on the other hand, the class of workman usually employed in America works harder and more intelligently, and, further, a little greater care is generally taken in the design of the towers to save as much labour as possible in erection, since it is realised what a serious item is involved in the labour of erection.

Several types of clamps designed to hold the wire and to release it after a certain pull is reached have been evolved; but though they may operate well under test, their action on the line after they have been exposed to the inclemency of the weather for some time is exceedingly doubtful.

This led one of the authors to design a flared or bell-mouthed sleeve wire-holder, as shown in Fig. 8. The sleeve has an inside diameter

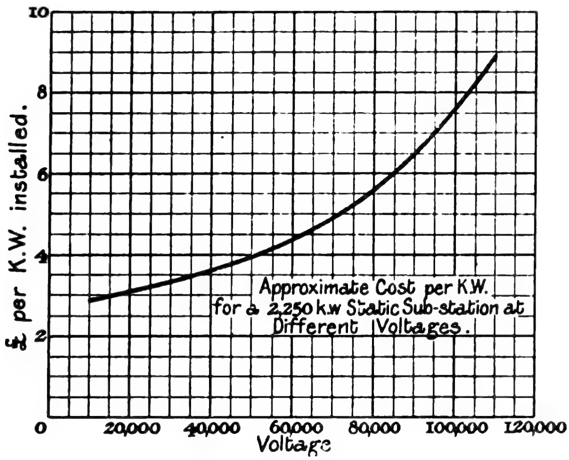


FIG. 7.

two or three times greater than that of the wires it holds, thus imposing absolutely no stress on the towers in case of wire breakage. The design shown is entirely preliminary and for experimental purposes, but it might be easily adapted and made much cheaper. The slot underneath, with the projection immediately above it on the upper half, is provided in order that the wire might be tied, in the usual way, by light tying wire, at points where a noticeable change in grade takes place.

Since the adoption of these holders on one line an unprecedented and severe flood caused the wreckage of a dead end tower. No harm, however, was done to the neighbouring towers, all the wires slipping through these sleeves and preventing any stress on the adjacent towers. Had the towers not been provided with this or a similar method of relieving the tresses, there seems no doubt that the giving

way of all the wires would have caused serious damage to the neighbouring structures.

Before leaving this section, the authors would draw the attention of those interested in this flexible method of designing lines to the necessity for care in its application, and they are of opinion that the success with which it has so far met is largely due to the more than usual care in considering the mechanical aspects of the line as a whole. It should, however, be remembered that this system has definite weight limits below which it is inadvisable to venture, otherwise the life of the line may be seriously reduced and other mechanical advantages sufficiently interfered with to seriously damage this type of construction, both from an engineering and a financial standpoint.

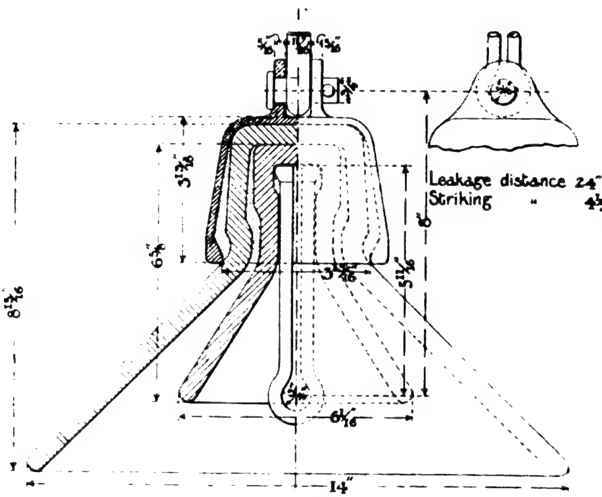


FIG. 9A.—Section of a Locke Suspension Type Insulator.

Insulators.—On account of the fact that insulators of the disc or suspension type (Fig. 9) as compared with the pin type are easier to construct, less fragile, and can easily be made of very great mechanical strength, they are now universally adopted for high-voltage work. Those most commonly employed are designed for working pressure of from 18,000 to 30,000 volts per disc, and have a wet flash-over voltage in the neighbourhood of two and a quarter times this value. The illustrations (Figs. 10 and 11) show strings of disc insulators of well-known types under a flash-over test.

When testing a string of suspension insulators dry, the voltage will divide in accordance with capacity effects, and when tested wet, in accordance with resistance effect. For instance, in a certain dry test one disc alone withstood 90,000 volts, and the addition of other discs

FIG. 8.—Flared or Bell-Mouthed Sleeve Wire-holder.

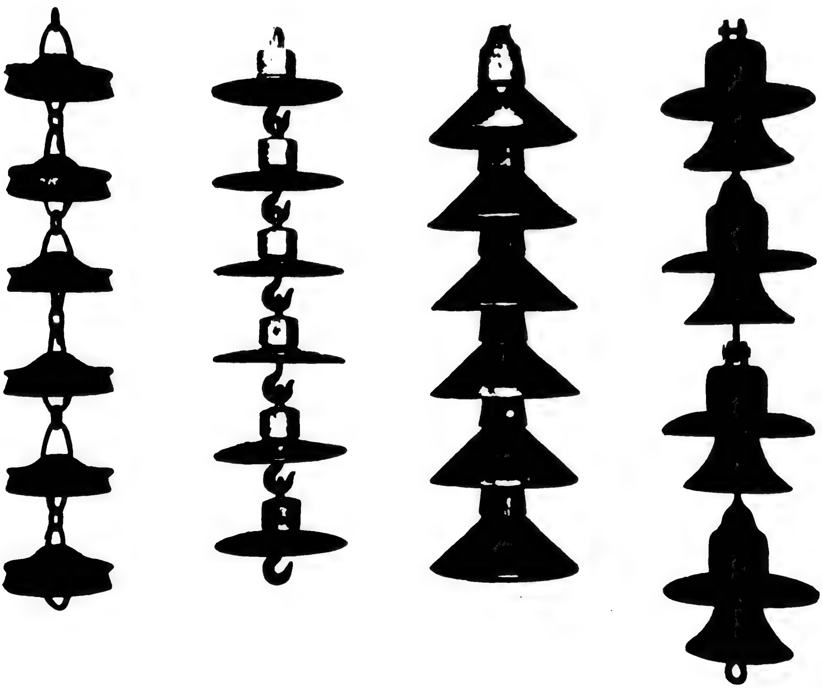


FIG. 9.—G.E., Thomas, Locke, and Lima Suspension Type Insulators.

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FIG. 10.—A Wet Flash-over Test at just under 300,000 Volts (Thomas Insulator).

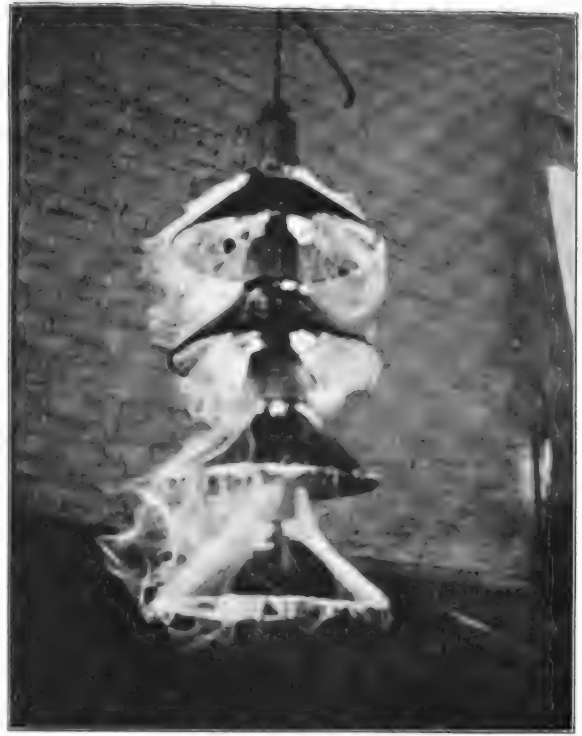


FIG. 11.—A Wet Flash-over Test at just under 300,000 Volts (Locke Insulator).

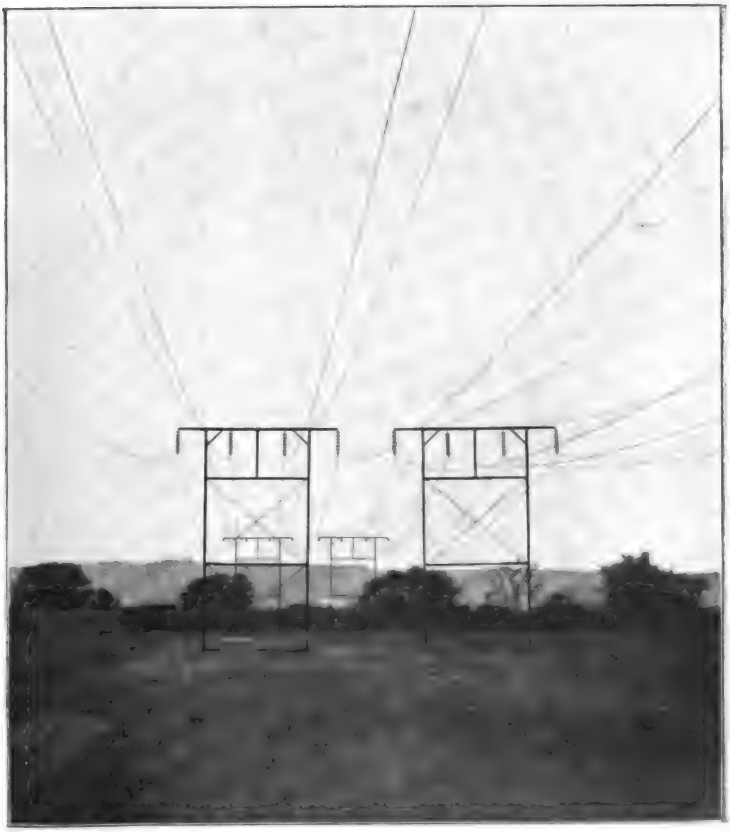


FIG. 12.—Experimental Flexible Tower Transmission Line.

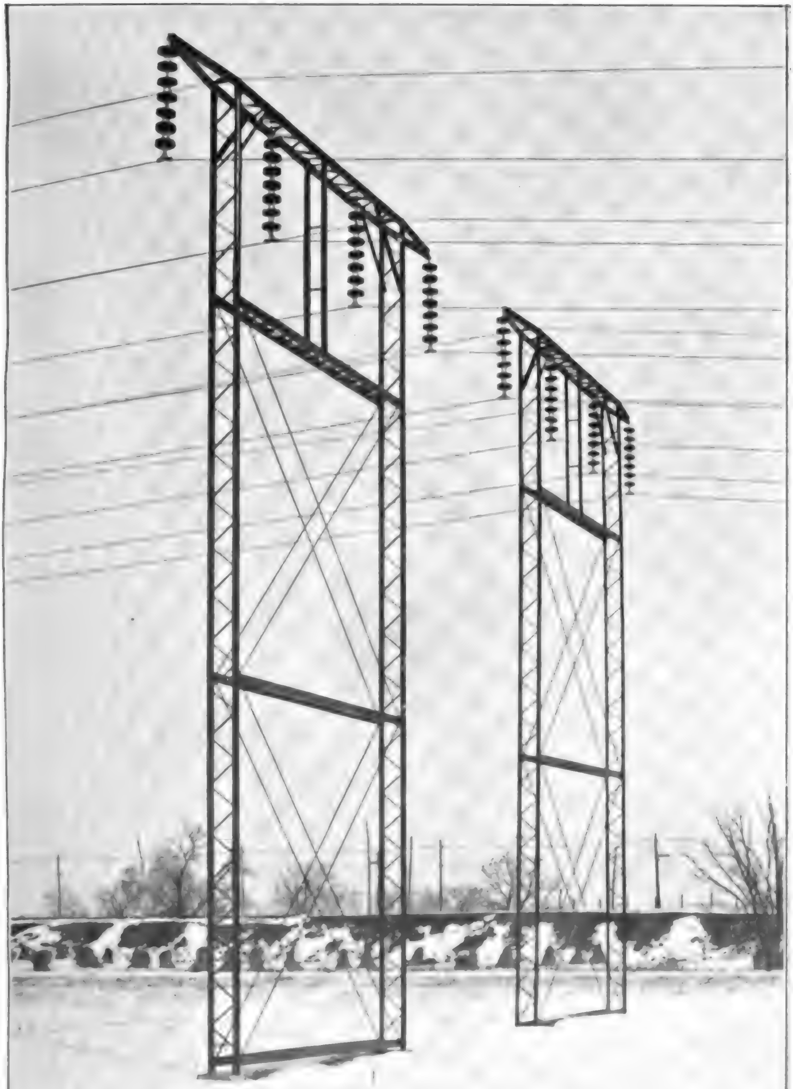


Fig. 12A.—Side View of Intermediate Transmission Towers of Flexible Tower Transmission Line shown in Fig. 12.

up to five gave a flash-over per disc when added one at a time, gradually reducing in value until the addition of the sixth disc increased the flash-over of the whole string only 30,000 volts, or one-third the dry flash-over for one disc alone.

In the wet test, however, the addition of units from one to six gave a very fair approximation to 45,000 volts per disc as each was added, the string of six breaking down at a wet test of approximately 270,000 volts.

In the design of these suspension insulators the fundamental principles must be kept in mind, namely, that the charging current varies with the electrostatic capacity and the resistance varies inversely with the electrostatic capacity; therefore a successful insulator should be designed to have minimum electrostatic capacity since high resistance and low charging current are required. Suspension insulators, with their fittings, should be in general designed of such strength that the line wire will break before they are damaged, and several of the best known makers supply insulators guaranteed to withstand a pull of 15,000 lbs. One important feature should not be lost sight of, which is that, in case of wire breakage, the full suspension length is thrown into the neighbouring span, the sag of which is thereby greatly increased, which results in reduced stresses on the cross-arms. In estimating this reduced stress it may be calculated as though the span into which the extra length is thrown were fixed firmly at the other end, and then, since the adjacent towers may be similarly supported, the actual reduction in stress will be between 40 and 60 per cent. of that calculated.

Corona Effects.—Fig. 12 shows an experimental transmission line erected in Schenectady, New York, for the purpose of investigating extra-high-tension phenomena, more especially the effects due to static or corona discharges, and the way in which they vary with climatic conditions, size of wire, etc. The phenomena obtained from these experiments were largely investigated in connection with special transmission projects, and have been fully borne out under actual conditions of operation.

The curve Fig. 13 illustrates the way in which the corona discharge increases with increase of electric pressure for a given wire when all other conditions are held constant, and the illustration (Fig. 14) shows the appearance of the same cable on a dark night when operating at a pressure slightly above the knee of the curve.

It is impossible at this time to enter into the abstruse phenomena of corona, but investigations have shown that the work of earlier investigators is only true under certain particular conditions, and that each case must be taken up separately and examined with the utmost care. It is known that the amount of discharge, *i.e.*, the loss for a given length of wire, varies with the elevation of the transmission line above sea-level—that is to say, the barometric pressure, the size of wire, the spacing of the wire, the condition of the atmosphere, the percentage of moisture, etc.

A curious effect of the sudden increase of loss after the critical voltage is reached has been the design of high-tension lines operating at a voltage only slightly below the critical point. Any induced surges or other high-tension phenomena are thus automatically dissipated in the form of corona discharge between the wires, and the line acts as its own safety valve. Lightning trouble on such lines is therefore comparatively small, partly due to this reason and partly to the high factor of insulation employed in the apparatus operating on such systems.

Transformer apparatus especially is particularly free from the effects of lightning. When lightning trouble causes flash over on the

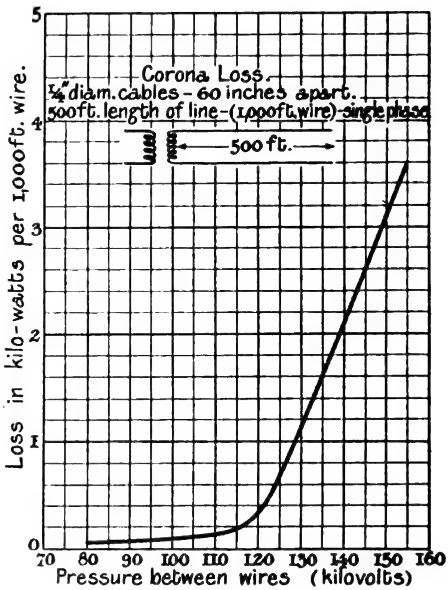


FIG. 13.—Corona Loss.

lines with pin-type insulators it usually results in broken insulators, for the higher the line voltage is the greater the tendency for the arc to hang on and rupture the insulator. This breakage of line insulators has been greatly obviated by providing an earthed metal ring round each insulator. This permits of the arc being transferred from the metal pin supporting the insulator to this ring, and thus the fracture of the petticoats of the insulator is eliminated.

The general practice is to use a ground wire for the protection of the line itself, and lightning arresters of the electrolytic type for the protection of the station. In general, however, troubles from lightning are noticeably less on the very high-tension transmissions since the normal voltage is so much nearer that of the static voltage induced

and the insulation of the apparatus is heavier. Further, in case of malicious short circuiting, the current is usually of small magnitude, and can be more easily handled by the protective devices.

Continuity of Service.—In the majority of cases a transmission line is of small commercial value unless continuity of service can be assured. The causes of interruption may be divided into three classes, viz.: (1) mechanical failure; (2) mechanical failure following electrical causes; (3) wilful damage.

Mechanical failure is, of course, due fundamentally to insufficient strength in some part of the construction. It may be caused, however, by accidents which could not have been foreseen. The chief causes for this trouble are land slides, severe floods, deposits of ice on wires, either alone or accompanied by very heavy winds, or even by ordinary climatic conditions if inadequate foundations are provided.

In England trouble from land slides and floods is not to be feared, since the geological and weather conditions have been studied and carefully recorded for very long periods, so that there is ample data at hand for the designer. A deposit of ice may occur at times in certain parts of England and somewhat more frequently in Scotland, though it is very much to be doubted whether it will ever occur to such a serious extent as is prevalent in certain parts of the United States. Hence the following comments, as the results of exhaustive investigations by the authors into the occurrences of this phenomena, may be of interest.

(*a*) Ice forms equally freely on wires whether they are alive or dead up to an operating voltage of 110,000. This statement assumes, of course, that the wires are not operating at a large enough load to warm them. The largest ice deposit noted was one of 5 lbs. weight per foot length on a No. 4 B & S gauge (0·2043 in.) wire.

(*b*) Ice clings with considerable tenacity to the lines; for example, the wire may fall to the ground and the ice still remain attached.

(*c*) The ice coat may form in a circular, or lozenge-shaped section, and with the wire either in the centre of the deposit, or considerably displaced therefrom, depending on the weather conditions. The lozenge-shaped formation where it occurs with the longer axis vertical will give a greater wind area than that usually allowed in calculations.

(*d*) As the ice melts, it may drop off from all the wires of one span, and remain on those of the next span, thus giving an unbalanced pull on poles or towers.

(*e*) An aluminium line will collect as much sleet and ice as copper or steel lines of the same section, indicating that the factor to be considered is the exposed surface of the wire, and not the material of which it is made.

(*f*) It is quite possible for sleet to collect at 32° F., and the temperature afterwards to drop considerably, so that calculations made to determine the maximum stress in the wire should be based on a sleet deposit at the lowest temperature to be expected in the district under consideration.

(*g*) The ordinarily well-constructed line, that is properly maintained, need not suffer strain from the stresses due to the formation of ice. In fact, though cases are on record of transmission lines having trouble from this cause, they are somewhat rare. The reason for this is, without doubt, that a conservative allowance is made in designing and building the line. For districts where this trouble may occur, in general, no wire smaller than a stranded one of equivalent section to No. 4 B & S gauge (0·2043 in.) should be employed for the long spans used in power work.

In England it is easy to obtain reliable figures as to the maximum wind velocity to be expected in any district, and it should not be forgotten that the pressure resulting from high winds increases very rapidly with a slight increase in velocity. In general the highest wind velocities occur during the winter and spring months, that is to say, during the periods when deposits of ice on the wires are possible. The weather conditions in the United States are more severe than those in England, but the usual allowance there is ½ in. thickness of ice all round the wire with a 65 mile per hour actual wind velocity occurring at the same time, or ¼ in. ice with an actual wind velocity of 77 miles per hour.

It is an interesting fact, borne out by long experience, that conductors of the same length and equally taut, will swing synchronously in any wind *if the line is properly designed.* Thus there is practically no danger of crossing or short circuit in the case of long spans.

The question of foundations for transmission line structures is one which has frequently not received sufficient attention. Where the structures are exposed to floods accompanied by floating ice, a regular crib work base should be used, such as would be employed in the case of harbour work, breakwaters, etc., with glancing timbers. For cross-country construction in good soil concrete foundations are practically never used in the United States. The ground stub is buried to a depth of about 6 ft., and a cross-piece, consisting of channel section about 1 ft. wide by 2 ft. long, is found to be sufficient. For swampy ground concrete foundations are generally desirable, and if the ground is very soft and the swamp deep, it may be necessary to resort to pile-driving.

The foundations of steel *poles* are frequently rather difficult to manage, especially if a heavy line or a large number of light lines are carried. The tendency is for a steady wind blowing on one side of the line slowly to move the poles out of the vertical, and though, if the foundations are properly made, this can never be serious, yet it greatly detracts from the appearance of the line. At corners, and also at angles in the line, this is, of course, much more liable to happen, and ample bearing surface should be provided, both at the extreme base of the pole and also near the earth surface, in order to withstand the leverage.

Mechanical failure may occur due to electrical causes, when heavy short circuits take place, or with a sudden electrical disturbance which causes a power arc of sufficient intensity to sever the wires, or damage

FIG. 14.—Appearance of Corona on a ¼-in. Cable at Night, Operating at Pressure above Knee of Curve, Fig. 13.

parts of the towers. The most frequent origin of this trouble is lightning discharge, though the very high-tension lines are largely free in this respect. The considerations given in the following items should receive the close attention of those interested in this subject.

1. In considering the district through which the transmission line is to pass, a careful examination should be made of the topography of the country, and districts especially subject to lightning should be, as far as possible, avoided. It is generally preferable to run along a valley instead of over hills, when feasible.

2. Continuity of service will best be maintained by building two separate lines, which should run as far as possible apart. It would seem advisable that the distance between lines should be at least 1 mile, and as much more as practicable.

3. Experience shows that a ground wire is of undoubted value, and better results may be expected from two than from one. They should be placed as far above the copper wires as is practicable. The overhead ground wire should be connected to the earth with great care at every tower where steel construction is used, and at every third pole, at least where wood construction is used.

4. To provide for cases of direct lightning stroke, it is very valuable to have a lightning rod on each tower. These rods need only be made of light material, and should extend at least 6 ft. above the tower, and more if practicable, and should have sharp points.

5. A liberal factor of safety should be allowed on the insulators. This is a part of the line where it will be found profitable in the long run to spend plenty of money. The tests on the insulators should, of course, be made under dry and rainfall conditions, and the proportion which the flash-over value bears to the working voltage of the line depends on the operating voltage. In the authors' opinion, it should always be considerably greater than twice the line voltage.

6. For lines operating at the higher voltages, the critical corona discharge value should be borne in mind, and the line designed to operate slightly below this point. In this way high potential discharges will then be automatically relieved, as previously explained.

7. Grounding of the towers should be done very thoroughly, and when they are placed in foundations of concrete, their steel legs may be allowed to pass below the concrete foundations into the wet earth.

8. Ample spacing should be used for all high-tension transmission line wiring. A good rule which holds between 30,000 volts and 100,000 volts is 1 ft. per 10,000 volts (*e.g.*, 40,000 volts, 4 ft.; 70,000 volts, 7 ft.) but this is modified in some cases by mechanical considerations.

9. A number of other expedients may be employed to meet mechanical trouble at points on the line where there is reason to suspect special danger, such as the employment of wooden cross-arms (if the climate is dry enough to permit of their use), or protection of the insulators by the double-ring method.

The cause of failure given as due to "wilful damage" is, of course, special and largely local. The chief trouble is due to the use of the

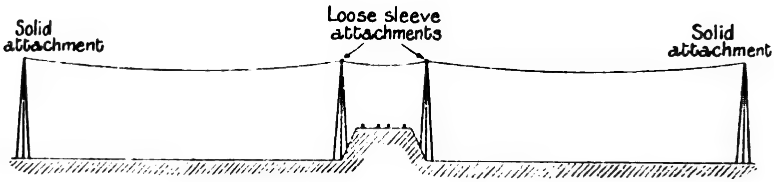


FIG. 15.—Protection of Railroad Crossing.

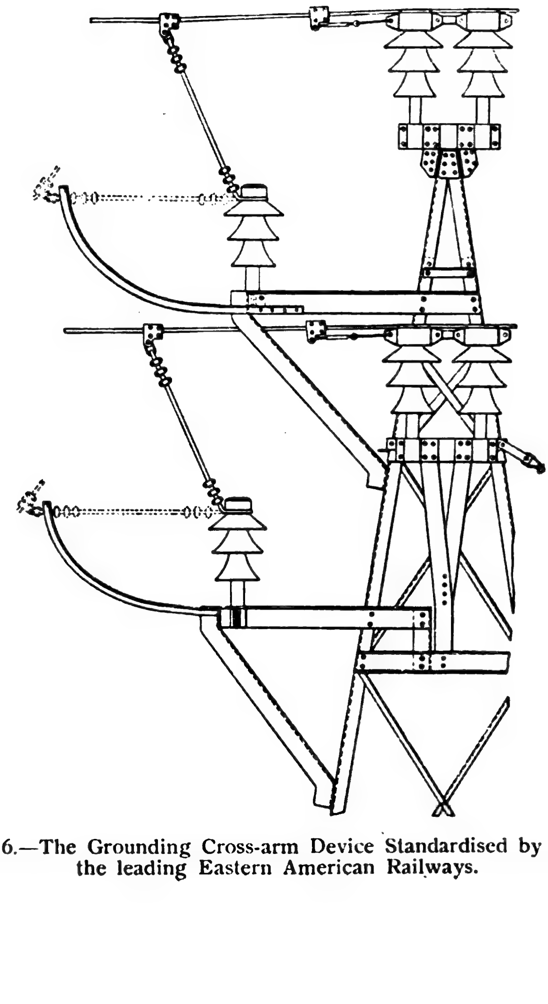


FIG. 16.—The Grounding Cross-arm Device Standardised by one of the leading Eastern American Railways.

insulators as targets by would-be rifle experts, and some of them are only too accurate in their aim, to the annoyance of the unfortunate man responsible for the maintenance of the line. Cases are on record where the overhead line has been short-circuited to throw out the automatic circuit breakers, and then torn down by mule teams to be sold as old copper. Again, dismissed employees have vented their grudge against the operating company by cutting the wires and otherwise interfering with the operation of the line. Such annoying occurrences can, of course, only be dealt with as they occur, at the discretion of the local management; still they have to be foreseen, and emphasise the necessity for a duplicate transmission line some distance apart.

Protection of Highways, Railways, Telephone Lines, etc.—Owing to the conflicting interests which have at times controlled the railways, power companies, tramways, and telephone systems in the United States, few branches of transmission work have received more careful attention and will better repay the study of those interested than the protection of highways, railways, and telephone lines at points where they are crossed by high-tension electric power lines.

Perhaps the best approved methods of protection adopted in the Eastern States for railways and highways are the grounded cross-arm device, and the system which depends for its safety on very rigid mechanical specifications for the crossing span. The method first insisted upon by some of the leading railways was that the lines must be carried above a steel bridge structure spanning the railroad. This is now realised to be unnecessary by all parties concerned, while the grounded cage net for highways is found to be a source of almost as much danger as that which it should guard against. In addition, the expense is unwarranted in view of the fact that better and cheaper methods are available.

An ingenious system which has been used is illustrated in Fig. 15. In this system the span is supported immediately on either side of the railway or highway, and the spans on either side of this crossing span are of extra length. The two crossing poles carry the necessary insulators, etc., but the wire is not tied tightly to them, but is supported in such a manner that in case of breakage it will readily slip through and be pulled clear by the longer spans.

All the above systems of crossing spans are guarded by strict mechanical and electrical specifications into which it would be tedious to enter here. These deal with the clearance, alignment, type of support, nature of steel or wood, foundations, guys, cross-arms, insulators and hardware, wires and cables, messenger cables, anchor devices, protection and grounding, etc. Further, the details are specified with regard to the load basis (dead load, ice load, and wind load), the breakage conditions under which structures must remain standing, the factors of safety, temperature limits, thickness of material, and such other items as are usual in steel work. With regard to the telephone crossings, these are slightly different.

APPENDIX I.

Steel Tower Line.

Cost per Mile—3-phase Twin Circuit with Ground Wire.

Voltage of line	50,000	60,000	70,000	100,000	125,000
	£	£	£	£	£
Towers	288	288	288	290	330
Insulators	33	40	60	65	72
Sleeves, guy clamps, etc., wire clamps, ground wire, additional for crossings, etc. ...	25	26	27	35	36
	346	354	375	390	438
About 5 per cent. for extras	17	18	19	20	22
Material, total, say ...	363	392	394	410	460
Labour, average ...	79	98	98	100	100
	460	470	492	510	560

APPENDIX II.

With a view to compressing as much useful information in this paper as possible, the authors have added as an appendix the two following specimen specifications, the one dealing with the concrete case of the towers for a 100,000-volt line, and the other with the insulators for a line operated at similar pressure.

Specification for Steel Transmission Line Towers.

General.—These structures are to be used for a transmission line of approximately 150 miles in length in a sleet district.

The structures and cross-arms covered by this specification are to be of steel, and will be used to support the insulators, conductors, and ground wire for an electric power transmission system operating at 100,000 volts.

The structures are to be designed to support :—

Six line conductors of stranded hard-drawn copper wire or wires having an area equivalent to No. 00 B. & S. gauge (0·3648 in.), and also a ground wire raised above the line conductors to such height that a line drawn from the ground wire to the outermost conductor will give an angle not greater than 45° to the vertical. The ground wire or wires to consist of ⅜-in. Siemens-Martin double galvanised stranded steel cable.

The conductors must be separated from each other by a distance of at least 10 ft., and a sag of 18 ft. will be allowed on the suspended wires. A tower spacing of 600 ft. is proposed, and the minimum clearance between the lowest live wire and the ground is to be 25 ft.

No member of the towers is to be made of metal of less than $\frac{3}{16}$-in. in thickness.

Metal steps are to be provided to within 8 ft. of the ground so as to facilitate the ascent of linemen, and in general, the construction of the towers shall be such as to permit of linemen ascending to any circuit with safety while the other circuit is alive.

The riveted sections of the towers shall not be of such size as to interfere with their being readily assembled in the field by means of bolts and nuts.

The towers are to be furnished complete with the necessary fittings, cross-arms, ground wire clamps, bolts, nuts and washers, and no concrete foundations are to be used except for swampy ground or angles in the line.

Strength of Towers.—The assembled towers will be required to stand the following mechanical stress tests at the same time without distorting appreciably or causing any member to exceed its elastic limit :—

1. A horizontal load of 5,500 lbs. applied in the direction of the line. The load to be distributed evenly between any two cross-arms and to be applied at the point where the insulator will be located.
2. A horizontal side stress of 4,800 lbs., plus an allowance for wind pressure of 30 lbs. per square foot of the projected area of the tower. The total load to be applied at the centre of gravity of the wires and at right angles to the direction of the line.
3. A vertical stress at the point of attachment of the insulators of 1,200 lbs.

Protection of Metal.—All parts of the structure shall be thoroughly galvanised by the hot process after all punching, cutting, and other machine work is completed. For all threaded parts the sherardising process is preferred.

Painting with special metal paints, or with ordinary paint, may be estimated on, but if so, this must be clearly stated and the paint adopted must be approved by the purchasers' representative. Tenderers under this item must also agree to prepare parts of the tower with one coat of paint before shipment and the surface of members to be riveted together must be carefully painted before riveting.

Insulators.—Suspension type insulators are to be used and the wire is to be supported approximately 3 ft. 6 in. below the cross-arm.

Quality of Steel.—The quality of the steel used in the construction of the towers and cross-arms shall be in strict accordance with the latest

specifications for structural plate and rivet steel as adopted by the Association of American Steel Manufacturers.

Inspection and Test.—The purchaser is to have the option of having an inspector at the place of manufacture, who will have the authority to reject any or all poles, or parts, which do not adhere to the interpretation of this specification.

Specifications for Galvanising Steel.—The galvanising shall consist of a coating of zinc, evenly and uniformly applied. The zinc shall be so applied that it will adhere firmly to the surface of the steel.

Any specimen shall be capable of withstanding the following test:—

Test.—Not less than three pieces shall be selected for test from each tower structure, and they shall be immersed in a standard solution of copper sulphate for one (1) minute and then removed, immediately washed thoroughly and wiped dry. This process shall then be repeated. If after the fourth immersion there should be a copper-coloured deposit on the sample or the zinc should have been removed, the lot from which the sample was taken shall be rejected.

Standard Solution.—The standard solution of copper sulphate shall consist of a solution of commercial copper sulphate crystals in water. This solution shall have a specific gravity of 1·185 at seventy (70) degrees Fahrenheit. While a sample is being tested the temperature of the standard solution shall at no time be less than sixty (60) degrees Fahrenheit, nor more than seventy (70) degrees Fahrenheit.

Sherardising.—Sherardising is preferred for all threaded parts and may be quoted on for the whole structure. The test is to be the same as that given above for galvanising.

Alternatives.—Wherever a manufacturer can give a total price per mile less than would be given by following this specification completely, and with equal mechanical and electrical safety, the purchaser will be glad to have a statement of this alternative.

Contractors are reminded that the erection of this line in the field will embody a large proportion of the total cost of the line, and any features in their design which will economise in line construction may be drawn to the attention of the purchaser's engineers.

Specification for Suspension Type Insulators for a Line Voltage of 100,000.

Insulators.—The insulators shall be made of first class, evenly fired porcelain ware, each part and the complete insulator when assembled as a whole to be symmetrical and not appreciably warped.

Glaze.—The entire surface of the ware excepting those areas which are to be set in the cement and such areas as are necessary for supporting the ware in the kilns shall be uniformly coated with a brown or slate colour glaze at the option of the purchaser. This glaze shall be hard and firm, and free from grit.

Cement.—The cement used in assembling the insulators shall be of the best quality Portland, neatly run in and allowed to set until sufficiently hard for handling (at least twenty-four hours).

Testing the Design.—One sample of each type of insulator to be considered shall be subjected to the following tests, and the purchaser reserves the option to subject one out of every five hundred to the same tests.

Fragility.—Only designs will be considered which are examples of rugged construction, and so formed that there will be a minimum exposure of any fragile part to missiles from below. As a guide, the following test may be carried out :—

A single disc shall be suspended from a wooden beam 40 ft. above the ground, and the purchasers' representative shall stand 45 ft. from the base of the pole. The insulator shall then withstand eight charges of No. 6 shot and four charges of No. 4 shot without breaking. Each charge shall consist of $3\frac{1}{4}$ drams of smokeless powder and $1\frac{1}{8}$ oz. of shot Winchelsea Leader shell. The test is to be carried out with 12-gauge choke-bore shot-gun.

Mechanical Stress Tests.—After it has been decided from the electrical tests how many discs shall constitute a complete suspension unit, this number shall be attached in a string and supported from a beam, the string to carry at the bottom the same clamp which will be used to carry the wire, and a cable being inserted in this clamp, a load of ... * pounds shall be applied without rupture or signs of distress in any part of the string.

Electrical Tests.—Sufficient suspension discs must be strung in series to stand, without flash-over, a potential of 300,000 volts (sine-wave generator), this potential to be maintained for 15 minutes continuously. The same potential to be carried by this complete unit for 15 minutes when exposed to precipitation of 1 in. in five minutes under a 45° spray.

Throughout these electrical tests the string of insulators is to be supported on a metal cross-arm, and the voltage is to be applied between this cross-arm and a 5-ft. length of the transmission line cable which is to be used on the line. This 5-ft. length to be gripped firmly in the clamp in the centre, and projecting each side $2\frac{1}{2}$ ft.

At 1.2 † times the normal potential across the string (100,000 volts) there must be absolutely no sign of static discharge either on the insulator or any of the fittings ; nor must there be any sign of corona on the same parts visible to the eye in a dark room.

Inspection of Order.—Having decided upon the design, the entire order of the insulators shall be inspected and tested as follows :—

Mechanical Inspection.—A mechanical inspection shall be made of all insulators and those rejected which contain open holes or cracks in the glaze or porcelain. The inspector shall use a light-weight mallet to rap each part, and note by the ring the soundness.

Air Cells.—Occasional samples of the ware shall be broken to see that they do not contain air cells of foreign matter.

(*Continued on page* 586.)

* Depending upon the size of wire to be used.

† This arbitrary value of $1\frac{2}{10}$ represents probable maximum voltage on system due to usual fluctuations of load.

A LIST OF TYPICAL TRANSMISSION SYSTEMS OPERATING AT 50,000 VOLTS OR OVER.

Name.	Voltage.	Total Output.	Generator Rating.	Transformer Rating.	Frequency.	Transmission Line.
		Kilowatts.	Kilowatts.	Kilowatts.	Cycles.	Miles.
Animas Water Power Company, Durange, Colorado	50,000 Δ	9,000 (ultimate)	2,250	750 (single phase)	60	25
California Gas and Electric Corporation (Pacific Gas and Electric Company) *	60,000 Y	14,000 (De Sabla plant)	2,000 and 5,000	—	60	170
Canadian Niagara Falls Power Company	62,500 Y	82,500 (ultimate)	7,500	1,250	25	15
Central Colorado Power Company, Colorado †—						
Glenwood Development	100,000 Y	11,000	5,500	3,330	60	430
Core Canon	—	20,000 (ultimate)	—	—	60	
Boulder Development	100,000	11,000	5,500	3,330	60	
Connecticut River Power Company, Brattleboro', Vt.	66,000 Y	20,000 (ultimate)	2,500	5,000 (3-phase)	60	60
Edison Electric Company, Los Angeles, California, Kern River Plant ‡	75,000 Y	20,000	5,000	1,667 (single phase)	50	120
Electrical Development Company, Niagara Falls, Canada	60,000 Δ	95,000 (ultimate)	Three 8,000 Two 10,000	2,670	50	80

Grand Rapids Muskegon Power Company, Grand Rapids, Mich. (Croton Dam Development)	110,000 Δ	10,000	5,000	3,750	50	50
Great Falls Water Power and Townsite Company, Rainbow Falls, Mont.	102,000 Δ	21,000	3,500	1,200 (single phase)	50	2 circuits, 135 miles each
Great Northern Power Company	60,000 Δ	60,000 (ultimate)	7,500	7,500 (3-phase)	25	14
Great Western Power Company, California	100,000 Δ	80,000 (ultimate)	10,000	10,000	60	176
Guanajuato Power and Electric Company, Guanajuato, Mexico (Zamora Plant)	60,000 Y	6,750	Three 1,250	1,080	60	101
Hudson River Power Company—						
Between Ballston and Amsterdam...	60,000	—	—	—	40	20
Between Utica and Clark's Mills ...	60,000	—	—	—	40	8
Hydro-Electric Power Commission of Ontario	110,000 Y	27,000	—	750 and 1,250	25	150 (approximate)
Kashmir Jhelum River Plant	60,000 Δ	4,000	1,000	1,000 (single phase)	25	50
Mexican Light and Power Company (Necaxa Generating Station)	85,000 Y	50,000	5,000 and 10,000	Eighteen 2,000 (single phase) Six 6,000 (single phase)	50	169

* The capacity of the system, of which this is a part, is 67,000 k.w.

† Maximum length of any one line, 177 miles.

‡ Ultimate development of the Kern River uncertain. The Company is at work on other plants in the neighbourhood, and the total development will far exceed the present.

A LIST OF TYPICAL TRANSMISSION SYSTEMS OPERATING AT 50,000 VOLTS OR OVER—*continued.*

Name.	Voltage.	Total Output.	Generator Rating.	Transformer Rating.	Frequency.	Transmission Line.
		Kilowatts.	Kilowatts.	Kilowatts.	Cycles.	Miles.
Michoacan Power Company	60,000 Y	3,000	Two 1,500	1,080	60	75
Nevada-California Power Company ...	50,000	9,000	—	—	60	50
Ontario Power Company	60,000	70,000	—	—	25	200
Pennsylvania Water and Power Company, McCall Ferry, Pa.	70,000 Y	92,500 (ultimate)	7,500 and 10,000	7,500 and 10,000	25	2 circuits, 40 miles each
Puget Sound Power Company (Puyallup River Development), Washington	58,000 Δ	26,000	3,500	2,330	60	46
Rio Janeiro Tramways Light and Power Company	88,000	70,000	—	—	60	60
Shawinigan Water and Power Company ...	50,000	14,500	—	—	30	80
Southern Power Company *	100,000	61,500	—	—	60	140
Southern Wisconsin Power Company ...	44,000 Δ 70,000 Y (ultimate)	6,000	Four 1,500	Six 1,000 (single phase)	25	2 circuits, 70 miles each
Stanislaus Power Company, California (Sierra and San Francisco Power Company)	104,000 Y	40,200	8,500	2,233 (single phase)	60	100

Spokane and Inland Empire Railway Company	60,000	40,000	—	—	25 and 60	100
Taylors Falls Development (Minneapolis General Electric Company) †	50,000 Δ	15,000	2,500	900 (single phase)	60	40
Telluride Power Company (Grace to Salt Lake)	80,000	—	—	—	60	110
United Missouri River Power Company ...	70,000	35,000	—	—	60	100
Washington Water Power Company, Spokane, Washington ‡—						
Post Falls	60,000 Y	13,000	2,250	2,200	60	260
Little Falls	60,000 Y	20,000	5,000	5,000	60	
West Kootenay Light and Power Company, Canada	60,000 Δ	18,000	4,500	—	60	—
Winnipeg General Power Company, Manitoba, Canada	60,000 Δ	22,500	1,000 and 2,000	830 and 1,800	60	65

* Ultimate capacity, 140,000 k.w.
† Ultimate capacity, 20,000 k.w.
‡ 30 miles of additional line under consideration.

NOTE.—There are, of course, a number of lines that have been constructed, or else are not yet quite completed, for ultimate operation at over 50,000 volts. As they are at present operating at lower voltages they are not mentioned here. The reason for the very high voltages employed on some lines of short length (*e.g.*, the Great Northern Power Company) is that extensions are of course in view, and the wise engineering policy has been adopted of operating from the beginning at the full pressure that the line will have to work at ultimately.

Puncture Test.—Every disc shall be tested for ten minutes continuously, with the voltage held just below the arc-over point.

General.—The insulator makers shall be required to furnish all facilities, equipment, and labour for making tests and inspection as specified above, and shall at all times allow free access to such facilities and equipment by the authorised representative of the purchaser until the entire order is inspected.

The insulator makers shall agree to deliver to the purchaser's representative finished discs at the rate of ...... discs per working day continuously after arrival of said representative at the insulator factory, in response to a written notification from the insulator makers that the order is ready for inspection and test.

Boxing.—Each complete string of insulators forming one complete suspension unit shall be shipped separately in a barrel or box, and the purchaser agrees to notify the contractor as to the proper shipping instructions within three days after the inspection begins.

DISCUSSION.

Mr. Jackson.

Mr. D. C. JACKSON (President of the American Institute of Electrical Engineers): The subject of high-tension transmission is one of great interest to America, and it is therefore a peculiar pleasure to me to be here this evening at the reading of these two interesting and valuable papers. The reasons for the particular interest of America in this subject are perhaps partially manifest to you; the large water-powers of the nation are needed, and they are needed at centres of utilisation that in many instances are far removed from the waterfalls themselves. There is another set of reasons which are more peculiar perhaps to American conditions. While we have great water-powers we have also great coal-mines, as is true of other countries, but America is a very large country and the coal-mines in many instances are remote from the important centres of manufacture and the centres of utilisation. Consequently we have the problem of getting the energy of the coal to the centres of utilisation, and while we must admit that perhaps the cheapest method of transporting the energy of coal to a distant centre of utilisation is by hauling the coal by rail, providing the grades are light, yet in a great many instances the grades are heavy. Then we find that transmission by electric current on a wire may be very desirable—and accompanying that we have this proposition facing us: The steam railroads are apparently moving towards the electrification of their systems, and it is now being thought amongst those who are, perhaps, a little radical in their engineering views, and perhaps a little ahead of their times, that great power-generating plants, of perhaps a quarter of a million horse-power each, may be erected at various intervals, consisting of steam-turbine generating stations near the coal-mines, and be utilised to sell power to the railways and to the manufacturing centres, in conjunction with the water-powers, thus bringing ultimately into almost universal service in

the nation, the power from the coal-mines and the power from the waterfalls. Now, alternating currents have in a sense come into their own for this purpose of high-voltage transmission ; at least they have come to play a tremendous part, due to the fact that it is so easy to wind large alternating-current generators for quite high voltages, so that the magnitude of the currents will be within reason for the purposes of controlling in the switch houses, and it is also easy to make transformations to still higher voltage for transmission purposes and then retransform at any convenient point for a sub-station or sub-stations, as they may be located along the line. Mr. Jackson.

Direct currents will apparently always play a large part. It is dangerous to prophesy, but they seem to have found a large place for distribution purposes, especially in the larger cities. But even in the large cities we have come to what formerly was known as high-voltage transmission by alternating currents, because in most of our large cities we now generate voltages close upon 10,000, perhaps 13,000 volts. One of the great cities in America has transmission at 20,000 volts. The transmission is by underground cables in many such instances. In other words, we have gone to underground cables with voltages which were beyond the reach of practice on overhead lines a few years ago, and that is making it possible to do what I understand your honoured President planned and tried to do some years ago when he was ahead of his day, that is, to furnish the entire power supply of a great city from comparatively few power centres ; from power houses with individual capacities of perhaps some multiple of tens or even hundreds of thousands of kilowatts. The power house that has 100,000 k.w. of generating capacity in actual readiness for service is perhaps still a unique institution in the United States, but it will soon be one of a number. But in those instances of the American cities here referred to, a great part of the power is utilised as direct current, while the primary generation is by alternating current.

As illustrating the way in which we have come to look upon the high voltages with comparative satisfaction, I will speak of one instance, which is somewhat of a commonplace, namely, the service for the interurban electric railways, as they are called in the United States. The interurban electric railways run from village to village, and city to city, sometimes being of relatively small length, but in some instances being of considerable magnitude. One system has some 600 or 800 miles of main track, another system has 400 or 500 miles of main track, and so on. Where these long systems are direct-current railways operating at 500 or 600 volts, the power is usually transmitted by means of alternating currents generated at conveniently located large power houses, the generators being, perhaps, 2,500-volt generators, perhaps 5,000-volt generators, or perhaps 13,500-volt generators, as the case may be ; but the power is transmitted to converter sub-stations at from 25,000 to 60,000 volts, and the transmission lines are handled by ordinary electric railway employees who have been brought to a knowledge of

Mr. Jackson.

how to handle electric lines. Ten years ago, those of us who were most familiar in the United States with high-tension transmission of power would scarcely have undertaken to put 60,000-volt lines, and we would have hesitated to put 25,000-volt lines, in the hands of any but very skilled men; but to-day we do not hesitate to put 35,000-volt lines in the hands of men who may be called unskilled.

Now we are facing the necessity of raising the limit of the voltage. The limits of practical voltage are set by various engineers who believe they know what may be practicable; some put the practicable working limit for the future as low as 200,000 volts between wires, some say 300,000 volts, and if the limit can be pressed to 500,000 volts it will make it possible, I think, to couple almost any power station in the United States with almost any other, and from that point of view it seems to me almost necessary for us to find a way. However, there are difficulties with the present practicable forms of line construction. If we go above 120,000 volts the losses due to corona and convection current between wires at the now practicable distances apart are really startling, especially in the higher altitudes in the upper plateaus of the country. More must be learned in regard to the actions of the electrons, or whatever it is that causes the trouble, before we are able to go much further than practice has yet reached. However, I have confidence in the ability of the engineers of the world to make the necessary discoveries and inventions to carry power transmission on to a very much wider limit than it has yet reached.

Mr. Welbourn.

Mr. B. WELBOURN: I think possibly both the papers are slightly misnamed, in that they deal with high-tension transmission and seem to take it for granted that that transmission is by overhead lines only, and that there is no question of transmission of power for any considerable distance by means of cables. I only mention that in passing, because there are certainly makers on this side of the Atlantic who are prepared to build cables for 30,000 volts alternating-current transmission, 3-phase, or for continuous-current transmission at 100,000 volts. Mr. Taylor, in his paper, has, I think, hardly done sufficient justice by his passing reference to Mr. Thury's work in the transmission of power by the direct-current method. The Moutier-Lyons line is a notoriously successful one and is operating at present and has done so for something like seven years past, at a pressure of 58,000 volts. I think the most important point for us engineers here to-night is possibly to consider what is the effect of the papers on English practice in transmission pole-line work. In the neighbourhood of London there is very little of it, but in other parts of the country, such as Newcastle, Lancashire, Yorkshire, and Scotland, there is a very considerable amount of pole-line work being carried out, and up to the present it has been almost entirely carried out by means of creosoted wooden poles. Now it makes one pause when one sees statements in both papers that the average life of poles that one can expect is only twelve years. I think that must be referring to untreated poles only, because in England we are using well-seasoned, well-creosoted poles,

Mr. Welbourn.

and I am very much mistaken if the life will not be nearer twenty-five years than twelve. I hope that before this discussion ends we shall have statements from engineers from the Post Office and the National Telephone Company, because they have really reliable data to go upon. Another point brought out in the paper is the question of the length of spans. In this country, so far as I know, the longest spans are 80 yards, and those are commonly employed now. The longest individual span I know of in this country was one I put up three months ago, 368 ft. long, but that was quite a special case; to get over a wayleave difficulty we had to jump a field.

I notice that neither of the papers deals with the question of the automatic protection of the lines in the event of a fault. In this country, both for underground systems and also for overhead systems, the Merz-Price protective gear is being very extensively employed. I do not propose to go into the merits of that gear to-night because it is very well known to the members of the Institution, but I should like the authors to tell us in their reply whether this system is anything like that which has been applied in America to the protection of overhead lines, because this method of protection does give instantaneous isolation of a faulty section. The gear certainly operates within $\frac{1}{10}$ of a second of the fault occurring, and the lines are cut right out of the circuit, long before any synchronous plant that may be running can fall out of step.

I think that a very controversial point is raised by both papers on the use of the longitudinal earth wire on these poles. Both papers seem to take it for granted that that is a common and most useful practice. Some time ago I had a trip from the Atlantic to the Pacific, I saw a great many of these lines and made very particular inquiry on this special point from practically all the engineers who are operating lines in Canada, and I found that, instead of there being unanimity on that point, there was very great diversity of opinion. Some of the most recent lines that I saw were put up entirely without any continuous earth wire. Others that had them, condemned them root and branch. One engineer, who had lines both with and without, said that his lines were struck indifferently by lightning, and he certainly would not put up any more lines with a continuous earth wire. I agree with the earth wire for mechanical reasons, and for electrically bonding together the metal on poles, and also for earthing purposes for the prevention of shocks in the case of a breakdown of an insulator, but I consider that the longitudinal earth wire should be of the same material as the line wires themselves, and therefore have the same life. I think it is very questionable indeed whether we ought to put up a galvanised wire above copper or aluminium, because it may come down, and if the supply cannot be interrupted I do not see how the earth wire is going to be renewed. I hope the authors will give us more information upon that particular point of maintenance.

Then I turned to both papers seeking for information on the use of aluminium conductors for overhead lines, and I was disappointed

Mr. Welbourn.

not to find very much information about it. In England, I think one of the outstanding features of the engineering of 1910 was the sudden prominence which aluminium obtained and the tardy recognition of it by engineers. There is a very great deal of aluminium pole-line work being done in this country. The nearest one to London is that which we are putting up for the War Office at Aldershot. The sizes of aluminium now being used in this country vary from No. 14 gauge to 1·4 sq. in. section. I mention the lower figure, *i.e.*, the No. 14 wire, because about four months ago we had 15,000 yards of it to put up. We also put up 5,000 yards of No. 12 gauge wire. I believe it was considered rather a bold venture, because some years ago Mr. Trotter read a paper before the Institution of Civil Engineers, and in the discussion upon it Sir John Gavey gave his experience, when Engineer-in-chief of the Post Office, to the effect that some single aluminium wires that he put up in the Midlands, either for telegraph or telephone purposes, all came down with the first storm, every individual span breaking. Those were the early days of aluminium, of course, and most new industries have their teething troubles. In view of that experience I have watched very closely indeed the behaviour of this wire that has been put up. It has had several gales on it and a good deal of frost and snow, and up to date there is no increase in sag that can be measured, so that there is good reason to think that the improved production and improved methods of manufacture have got over those initial troubles. I do not speak too positively because the experience is only short, but the behaviour of it up to date is extremely good.

There is one further point I should like to mention in connection with Messrs. Matthews and Wilkinson's paper. The authors say that it may be taken for granted that the accumulation of sleet and snow on aluminium and copper wires is the same. On that point I have no experience whatever, but last week I had the advantage of a conversation with one of the most experienced operating engineers from Canada. He has aluminium transmission lines and has also had experience of copper, and he was very emphatic on the point that the aluminium does not collect as much sleet as the copper. I hope the authors will give us some further information in support of their statement.

ADJOURNED DISCUSSION, FEBRUARY 9, 1911.

Mr. Redman.

Mr. S. G. REDMAN: The subject of the papers appeals very strongly to the members of the Institution, particularly to those on the north-east coast, where a considerable amount of overhead transmission work has been carried out. Reference has been made in one of the papers to the 20,000-volt overhead system; and although these lines are not directly comparable with the extra high-tension systems described in the paper, or with the very long distances mentioned, it may be of interest to show on the screen at the conclusion of my remarks some examples of the work carried out round about Newcastle and Middles-

brough. On page 514 of Mr. Taylor's paper he makes a general statement to the effect that the voltage at the receiving end of a transmission line tends to be higher than at the generating end, and illustrates this by the diagram shown in Fig. 1. The diagram is certainly far from clear, if not incorrect, and the fact of the rise in pressure, though true in certain cases of transmission by underground cables, is not true of overhead lines. The only possible cause in the case of overhead lines for any pressure rise at the far end would not arise from the line but from the presence of over-excited synchronous plant in substations. The advantages of aluminium lightning arresters can be endorsed by the experience on the north-east coast, where several have been in use for some considerable time, and the number will be augmented very considerably in the near future. Turning to Messrs. Matthews and Wilkinson's paper, it is stated on page 574 that "conductors of the same length and equally taut will swing synchronously in any wind." In practice experience has unfortunately been the reverse of that. It is certain that under working conditions of ice and snow, wires erected equally taut do not remain so; with spans over 80 yards long they certainly do not always swing synchronously, and the spacing on the poles has to be appreciably increased to allow for this. On page 577 an arrangement is referred to for railway crossings. This arrangement, as shown in the illustration, would not be accepted by any of the railway companies in this country—at any rate, not by any railways on the north-east coast. It appears to be only of use if the conductor can be depended upon to break in the middle of the short span. If it were broken in the middle of the long span, one feels that the wire would sag and get unpleasantly near the railway tracks. The price curves given for overhead line work cannot be touched in this country, but then, of course, we do not work in such large mileages. The figures showing the number and extent of systems employing very high tension transmission which are given at the end of the paper are surprising to many of us, and we are grateful to the authors for bringing before us so many of the points which come into consideration on these very long lines. Mr. Redman.

Mr. A. P. TROTTER: One feature of these papers which distinguishes them from so many that we have before us is that they deal with foreign work. A great many of the papers read before this Institution are rather of the parish pump description, but it is a very good thing that we should hear of what is going on elsewhere. We may discuss these papers on engineering merits, but they are also of considerable guidance to those engineers who, having experience in British practice, may some day have to go to countries where work of another kind is wanted. These papers deal with high pressure—with higher pressure than we have in this country. It is well known that some Americans on first landing here are surprised at the small locomotives we have on our railways. They account for it by the fact that if we had larger ones they might run over the edge of our little island. The same sort of thing applies in respect to the transmission of electrical Mr. Trotter.

Mr. Trotter. energy. It is rather doubtful if we have transmission lines long enough to make it worth while working at these high pressures. High-pressure transmission means long distance transmission, and the cost per mile depends upon economic matters made up of several factors. Railway rates are composed of two principal factors : the terminal charges and the ton-miles. The cost of the terminal charges in a high-pressure line are very considerable ; the cost of the switchgear is about proportional to the volts, and expensive substations are required ; and I think it will be found that the terminal expenses of these very high-pressure systems would not be warranted on the short lines that we have in this country. With higher pressures everything is more expensive except the conductor. It is probable we shall not go very much further than 20,000 volts with ordinary alternating supply. Somebody said the other day in a discussion that in this country we are behind-hand as regards pressures and lengths of overhead circuits, due largely to the stringent restrictions of the Board of Trade. It may be so, I have not come across these restrictions myself. We have a limiting pressure for alternating current overhead work of 250 volts. Anything below that has to comply with certain regulations, and anything above 250 volts has to comply with another set. If it is 250, 2,500, or 25,000 it does not matter—it is a bad thing to touch. It has got to be safe, and that is all. When these 20,000-volt lines came along there was absolutely no difference whatever made in the Regulations from the 6,000-volt lines. The spacing of the wires and the insulators are different, but there are no regulations about them. Ordinary engineering practice will take care of that. In the use of these high pressures we are not quite so behind-hand as is supposed. It was our President who, twenty-two years ago, startled both England and the whole world by using 10,000 volts, and his concentric system of mains has been proved to be absolutely safe. Not a single accident to the public has been heard of so far as the 10,000 volts is concerned. Then, again, we shall not be so very much behind-hand shortly. Four years ago Mr. Highfield told us about the continuous-current high-pressure system, and I look forward with great interest to a 120,000-volt distribution to the West of London.

Mr. Taylor's paper starts off by referring to the old-fashioned, slow-going ways of this country, that we are a conservative country, but that the attitude of the authorities is gradually changing. I suppose he means the local authorities that give so much trouble with wayleaves. The next thing to which I wish to refer is the question of wooden poles *versus* steel poles. There, again, I think these papers are very valuable as showing what is done and what must be done in other countries. At the same time I do not think that we can go so far as one of the authors, who says that wooden poles are now practically a thing of the past. In America, where the process of creosoting is unknown and would be impracticable, they like to cut the poles down by the side of the line and put them up as they go. Of course wooden

poles would not be suitable for some of their work. Above 20,000 volts the construction would sometimes be such that wooden poles could not be economically employed. But they are not a thing of the past here. The question of the life is a thing which appeals very much to American engineers and other engineers. We hear of the life of wooden poles being put down at quite a few years—seven or eight years. In the discussion on Mr. Wade's paper at this Institution four years ago I gave a few extracts from Continental and American opinion as to the life of poles.* In the course of the discussion on that paper Mr. Wade put down the life of a pole at 50 years; that was perhaps a little too far; but Major O'Meara, in his carefully considered contribution to the discussion,† put down from 36 to 40 years as the average life of a creosoted pole, though he said that in certain soils a shorter life of 15 or 20 years was obtained. Now, 30 or 40 years ago the process of creosoting was probably not so elaborate as it is now, and the fact is that many of these old poles have not yet finished their life. Against that must be set our experience with steel poles. How long is a steel pole going to last in this climate? How often is it going to be painted, and is not the inspection to see that the painting is properly done almost as expensive as the painting itself? I suppose the poles will have to be painted every three or five years, so that steel poles are not quite as economical for our English purposes as they are in other places. Then, again, with regard to the height and span of poles, there is no limit of span that I am aware of; the Regulations prescribe for factors of safety, and those are taken into account on the span. Some time ago the idea of overhead conductors cables across the Tyne was discussed—about three-quarters of a mile span. I looked forward to that work immensely, but unfortunately the cost of the towers killed the scheme, and the cables had to be put in a tunnel instead. I discussed some time ago the question of slinging some cables across some of the valleys in South Wales. That would be a very nice job to do. There are no obstacles whatever in the form of regulations. Edmondsons allow me to state that they are shortly about to put across Hayle Harbour a high-pressure line with poles 146 ft. high with 600-ft. spans. That will be worth going to see. They will be erected very much in the same way as described here. So far as economy is concerned, tall steel poles do not appear to be worth putting up on cross-country work on agricultural ground. I have seen many designs, but they came to nothing. The cost per mile works out higher than wooden poles. Very long spans would mean higher poles to clear the ground, or very long arms for high pressures where a different construction is necessary. The question of flexible poles has been touched upon in the papers almost too briefly to be of practicable service. I think I perhaps went too much into arm-chair mathematics on the subject four years ago,‡ and it would be very useful if some practical engineer would go into

Mr. Trotter.

* *Journal of the Institution of Electrical Engineers*, vol. 39, p. 342, 1907.
† Ibid., p. 340.
‡ *Proceedings of the Institution of Civil Engineers*, vol. 169, p. 183, 1906–1907.

Mr Trotter. the question of flexible poles from the practicable point of view. The practical point is not the deflection of the pole, to which the authors refer; what we want to know is the stress which would be put upon the pole when it is pulled over by the wreck of a line, and on this they give no information.

Mr. Redman has already spoken about the wires clashing together, and this is a thing to be reckoned with. In a high wind the wires surge in big waves, which is a very serious matter, especially on the hillside. That brings up another question, namely, the binding of the wire to the insulator. One of the small details which surprised me most in the papers was that the authors referred to letting the wires run loose through the insulator. Overhead wiremen in this country have been giving most careful attention to the binding or clipping of the wires on to the insulators so that they cannot move a vestige. I know of one accident which was entirely due to the big ripples set up on the wire during a gale. This worked the binding loose at the insulator, and the wire becoming loose, fell against the pole, fired it, and softened the wire, which pulled out and broke. There are just two questions I would like to ask the authors—namely, whether wayleaves, which seem to be a trouble there, as they are here, are granted by the local authorities for the running of these lines alongside the roads as telephone lines are run; and whether, on the other hand, the railways will grant wayleaves for the wires to be run alongside on the property of the railways to avoid wayleaves on agricultural country.

Communicated: The steel poles which I had in mind were of the lattice type. Since the meeting I have seen some light tubular poles in Cornwall which seem to give promise of a longer life than a lattice, channel, or angle construction.

Mr. Peck. Mr. J. S. PECK: The papers under discussion are of special interest as showing the remarkable advances which have been and are still being made in the long-distance transmission of power. Mr. Taylor's paper in particular, which treats the whole subject in a very general way, shows not only the great problems which are involved in designing and installing a plant of this type, but also the very high order of engineering ability required to keep a plant of this kind in successful operation. Perhaps the most interesting questions on this subject concern the limit in the distance of transmission and the limit in voltage to which we can go. There is a financial consideration which comes in here which may be the determining factor in fixing these limits. It does not pay to transmit over a distance greater than that within which the load necessary to keep the station fully busy can be picked up. It is probable that at voltages below 200,000 distances can be reached within which the full load can be obtained for any water-power or any waste heat plant, or, in fact, for any type of plant that is likely to be installed. A very few years ago the pin type of insulator was the only one available, and it seemed at that time as if the insulator would be the limiting factor, and that it would not be possible to go

much above 60,000 or 80,000 volts. Then the suspension type of insulator was devised, and immediately the limits were increased 50 per cent., so that voltages from 100,000 to 120,000 are now in use, and even higher pressures are projected. There will undoubtedly be other types of insulators invented, and improvements made on the present type of suspension insulator, which will make it possible to go up to 200,000 volts or even higher. We shall also learn more about the laws which govern high-voltage transmission, but in any case it would seem that pressures in the neighbourhood of 200,000 volts will be sufficiently high to enable us to dispose of any power that will be generated at any one place without involving excessive costs for copper. Mr. Peck.

Turning to the papers, there are a number of points which might be discussed, but I will only touch on a few of those that have occurred to me. On page 510 Mr. Taylor refers to direct-current transmission, and states that in a short time direct-current transmission will be as simple as alternating-current transmission is at present. I do not know that alternating-current transmission is particularly simple just at present, but there is no doubt that, so far as the transmission line itself is concerned, direct current is ideal. The difficulty in insulating the generators and the motors has retarded its development. I should like to know whether Mr. Taylor has any particular system or any great improvements in mind which lead him to make this statement. On page 511 he refers to the ratio of the leading or lagging currents, and says that condensers may be connected in parallel to the line in order to improve the power factor. I do not know of any condensers which can be connected to a 100,000-volt line. It may refer to rotary converters or synchronous motors, but the meaning is not very clear. On page 514 he says that changing the size of the wires and the spacing of the wires has very little effect upon the inductive drop or the capacity current. That is true within limits. The inductance varies with the logarithm of the ratio of spacing to diameter of wire, while the capacity varies as the logarithm of ratio of diameter to spacing. There is an interesting relation which follows directly from the equation for inductance, namely, that if the diameter of the wire be doubled the spacing may be made twice as great, with the same inductive drop as previously; and the inverse of that is also true. This is very useful in taking these figures from tables where all the sizes and all the spaces are not given. On page 515 Mr. Taylor refers to the difficulty of obtaining good regulation when motors of 5,000 or 6,000 H.P. are switched directly in line. I do not think any one would attempt to run motors of that size directly from the circuit; there would be some form of flywheel equaliser installed in every case. On page 521 he refers to three 6,000 k.w. single-phase transformers with a 12,500-k.v.a. generator. I presume that the three transformers are connected in delta, with the idea that if one transformer fails the other two will carry practically the full generator load, otherwise I do not see why 18,000 k.w. in transformer capacity should be connected to a 12,500-generator capacity.

Mr. Peck. Mr. Trotter has referred to the question of the life of wooden poles. Mr. Taylor says that the life of a wooden pole is from 5 to 30 years, with an average of 12 years; and Mr. Matthews says that the life of a wooden pole is 12 years. I presume the climate as well as the treatment may have something to do with the life of the wooden pole. On page 538 Mr. Taylor recommends that lightning arresters be installed on the low-tension side of the power transformers to protect them against internal surges. Lightning arresters do not protect from internal strain as ordinarily meant; they simply limit the voltage above the earth, and, in any case, I do not think that lightning arresters on the low-tension side of large transformers are at all necessary, because the number of turns in the low-tension winding is so small with reference to the number of turns in the high-tension winding that it is possible to insulate every turn to withstand many times the voltage to which it is likely to be subjected. On page 540 Mr. Taylor refers to rotary condensers for improving the power factor, and intimates that the regulation will be greatly improved on account of the charging current, due to the capacity of the system. The capacity of the system does not help the regulation of the system, if by regulation is meant the drop in voltage from no load to full load. It simply means that at any particular load there is a higher voltage at the end of the line than there would be were there no capacity; but the rise in the voltage is fixed by the charging current and by the self-induction of the line, which are constant, whereas the regulation of the system depends upon the load and its power factor. If rotary converters are used some means must be taken for compounding the rotaries—that is, advancing the power factor as the load comes on in order to compensate for the increased drop in the line itself. It has been proposed by one engineer to use synchronous generators at the end of the transmission line. These generators are so excited that they supply the charging current to the line; thus there is a higher voltage towards the middle of the line than there is at the receiving end of the line. As load comes on the voltage on the generators at the receiving end would tend to drop, and the charging current would be fed from the generating end instead of from the receiving end, and therefore the voltage would tend to rise and so maintain something like a constant pressure.

A great deal might be said as to the star-delta system. Mr. Taylor deals with the matter on page 544 and mentions the fact that with the delta combination it is possible to use two transformers in the case of the failure of one. It is also possible to use two transformers connected, delta-star, if the neutral points of raising and lowering transformers are grounded; in fact, it would be possible to connect the neutral points of the two remaining transformers to the third conductor, and thereby transmit power to two-thirds of the normal amount at 57 per cent. of the normal voltage. The question has been raised as to why the delta connection should be used on both ends of the transmission line at the commencement of the service, with the idea of

raising it later on: why not connect the transformers in star, and ground the neutral at the commencement? In certain transmission plants which have been installed the engineers have gone right up to the limit of the insulators at the very beginning, and when the voltage limit of insulators has been raised new insulators have been put in and a change made to the star connection. By this means the voltage on the system has been increased by about 60 per cent. On page 539 Mr. Taylor refers to aluminium lightning arresters, and in that connection I may say that the only objection which has been raised to the aluminium arrester is that it must be recharged at more or less frequent intervals, as the coating of the plate dissolves; and while this recharging is a very simple process, it must be done regularly, in some cases every few weeks and in others every day or two, thus a considerable amount of attention is required. Mr. Peck.

Mr. H. W. CLOTHIER: A paper coming from so far across the seas as Mr. Taylor's is bound to introduce a good many novelties to us, and among these I find some terms and descriptions which I think are strange to British practice. For instance, the word "bushings" is used in connection with switches. Are these the same as we would call insulators? "Primary relays" are also referred to. Now, a primary relay is shown diagrammatically in Fig. 8, and it resembles a series trip coil, but in the text on the same page the words "primary relay" are used in parentheses after "electrically operated," thus inferring, as I understand the terms, that the relay has to do with the remote electrical control for closing and opening the circuit. With a view to uniformity I should like the above definitions explained; I would also like to know exactly the construction of a "differential" time limit relay, an example of which is shown in Fig. 2. The "arcing length efficiency," *i.e.*, the ratio of the sparking distance across the surface of an insulator to the sparking distance across air, would be a useful basis to work upon when comparing insulators, but the author does not give the actual efficiency of his insulators in figures. It would be interesting to have his records in this respect, although the figures are likely to vary considerably with the atmospheric conditions and the shape of the conductors. The "load dispatcher" in this country is called a "system engineer," and as this person controls the whole of the switching operations on the system, I think the latter is the most suitable term. I should be glad to have some more information from the author concerning actual breakdowns, the causes and the frequency of these occurrences. The author refers to the time taken in getting the system running after an interruption, and in one place he suggests the time of 2 to 7 minutes on systems operating hundreds of miles of line, and in another part of the paper 5 to 15 minutes for a system with one receiving station and one line of, say, 80 miles. I think even the latter is as short a period as one could possibly expect on any of the systems described in the paper. Unfortunately the author has entirely omitted to describe in the text the method of operating the system shown in Figs. 2 to 10. Time does not permit me to criticise Mr. Clothier.

Mr. Clothier.

in detail the five or six different systems of protection shown by these diagrams, but I think it would add to the value of the discussion if the author, in his reply, would deduce from the several diagrams he gives the method of connecting and protection that he would consider most desirable to adopt. Speaking generally, as far as one can gather from the diagram, the principal considerations have been given to protection with a view to anticipating the failure of the control apparatus; and although in the early part of the paper we are told that the weakest part of the system is the line itself, which would appear to be the part on which proper automatic protection is required, yet the author's protection systems seem to be designed with a view to accepting complete interruptions to the whole supply as inevitable and to getting away again as quickly as possible. A better principle is to construct the switchgear so that, in the event of a breakdown occurring anywhere on the system, the faulty part is cut out without causing a cessation in the supply. I believe the majority of the high-tension overhead transmission work in this country is protected in this way by means of the balance system of protection. I have described elsewhere the lay-out of protective gear on these lines.* I think in the practice of this country the ways of dealing with automatic protection of transmission schemes are more thorough than anything referred to in the paper.

With regard to the "ground wire" (or "earth wire"), it seems to me preferable to have it suspended underneath the load lines, and in this position it can be of assistance in the design of protective gear; one of the difficulties in the automatic isolation of faults being to obtain sufficient current to operate the relays in the event of a line remote from the power station falling to earth, and this problem is met by mounting the earth wire in such a position that the line in falling would strike it. I would offer as a suggestion the possibility of the "ground" line enclosing the pilot wire. The first question that appeals to one on reading the paper, considering it from a protection point of view, is what design one would adopt for 100,000 volts on lines 100 miles or so long. I admit that this problem would introduce many difficulties; for example, the capacity current in the pilot wire would be so great as to make the systems on which we have at present had experience out of the question. I feel satisfied, however, that, thanks to the study that is now being given to the question and to the experience that has been obtained here during the last six years, the difficulties are not insurmountable. The author refers to high-tension direct-current systems, and, as one who has spent a lot of time working out problems in connection with switchgear, I may say that I look upon the direct-current system as presenting an aspect of rest to the switchgear designer. The feature that appeals to me is that with alternating-current systems it is necessary to design apparatus to open circuit instantaneously when a short circuit occurs, whereas with a high-tension direct-current system a short circuit is a part of the method of operating, and there

* *Electrician*, vol. 66, p. 420, 1910; *Electrical Engineer*, vol. 44, p. 706, 1910

is no intentional opening of circuits under load. One of the main problems in regard to alternating-current systems at the present time is to open a circuit properly and at the right time. Mr. Clothier.

Mr. W. B. Esson : The papers which have been presented to us by Mr. Taylor and by Messrs. Matthews and Wilkinson contain a large amount of information, and when they appear in the *Journal* they will be very valuable to us because they bring into a small compass many facts. We have a lot of high-tension information scattered through all the technical journals, and the authors have really done us a service in bringing together all the data dealing with the last three or four years' work within a manageable bulk. We have heard a good deal from the authors of both papers on the subject of flexible poles. I think the term "flexible poles" is a misnomer, but the term has also been used by Mr. Trotter. When we speak of flexibility we mean that the particular object referred to yields to any external force, but the term does not imply that the particular object resumes its former condition when that force is removed. That is the difference between flexibility and elasticity. Mr. Guido Semenza, who introduced this pole into Italy, and who read a paper before the American Institute of Electrical Engineers on the subject in 1904, did not call it a flexible pole ; he called it an "elastic support," and that is really what it is, for the primary idea in devising this pole was not to get flexibility at all, but simply to save the cost of materials. In the first Italian lines the poles were made rigid to the same degree in all directions, and it was found that they were very expensive. It struck Semenza and other engineers that it was a great waste of material to provide for strength in the direction of the line under conditions in which normally no such strength was required. Running over flat country, with uniform spans, under normal conditions the pole had to resist only the wind force at right angles to the line, there was no strength required in the direction of the line, consequently a great deal of the expense in the construction could be done away with. What I want to emphasise is that elasticity was only an incident and not the original intention : the original intention was to save cost. But this incident was a very valuable one, inasmuch as the support made up in elasticity what it lacked in strength, and therefore when a wire broke there was no damage done, because the pole was capable of springing to the opposite side to a considerable extent, and when the strain caused by the broken wire was removed, it would go back to its former position without any harm. As regards the question of foundations, American practice does not seem to be very strict. The authors speak of the poles being put into the soil without, as I understand it, any attempt being made to get solid foundations. I do not know if I have read the papers aright in this respect, but we in Europe use very solid foundations. We put in great masses of concrete, so that there is no possibility of any movement of the earth such as Messrs. Matthews and Wilkinson describe in their paper. I notice that no reference has been made to the substitution of aluminium for copper in the lines. Mr. Esson.

Mr. Esson. Some time ago the cost of the conductor part of the line was much greater if aluminium was used, because aluminium was at such a high price, but now if aluminium is used instead of copper there is a saving of something over 20 per cent. in the cost of the conductors, which is a very great consideration.

Mr. Snell. Mr. J. F. C. SNELL: Aluminium conductors are referred to on page 513 of Mr. Taylor's paper.

Mr. Esson. Mr. ESSON: Quite right. I see that aluminium is mentioned, but it does not alter the point I was about to make. The point about aluminium is that although the conductor is half the weight for the same conductivity it is something like 30 per cent. greater in diameter, and there is consequently a greater amount of strain due to the wind pressure than there is with copper wire. At the same time it must be remembered that as the power to be transmitted becomes greater this factor of wind pressure is not so important, because, whereas in quite small wires the strain produced by the wind pressure may be something like four times as great as the strain produced by the weight of the wire itself, when we get to large wires the strain produced by the wind pressure may be only twice the weight of the wire. I do not consider that when we get to large sizes the question of wind pressure militates against the use of aluminium. Messrs. Matthews and Wilkinson refer to a rule for the distance apart of the wires, and they say it is a good rule. It is that a space of 1 ft. be allowed between the wires for every 10,000 volts, so that if we have a 30,000-volt line we have the wires 3 ft. apart, if 40,000 volts, 4 ft., and so on. I do not want to trouble you with ancient history, but I would like to point out that that rule was first suggested by me in 1905,* with certain limitations to the effect that the wires must not be closer than 2 ft., however low the voltage was. The rule has been across the Atlantic since then, and as it now comes back to us with a good character certificate attached to it, I suppose I ought to feel very happy. Another question to which I would like to call attention is the star and delta connections. In Messrs. Matthews and Wilkinson's paper a large number of examples of actual lines are given, and it will be observed that up to 60,000 or 70,000 volts the star and delta connections are about equal, but the curious thing is that when we get up to 100,000 volts the majority are delta instead of star; in fact, there are only one or two star. I should have thought that it was just when attaining very high pressures, in the vicinity of 100,000 volts, that advantage would have been taken of the star connection, because by that means with grounded neutral the pressure between the wires and earth is reduced to 58 per cent. of the pressure between the wires. That is to say, with a star connection the pressure between the conductors and earth is predetermined in such fashion that it can never exceed 58 per cent. of the pressure between the two wires, but with a delta connection the pressure between the wire and earth may be anything up to full pressure between the lines. I should have thought that, with the

* *Electrical Review*, vol. 57, p. 330, 1905.

high pressure, the star connection would have been adopted, and I should like to ask the authors whether they have any information as to why it is that in the very highest pressures the delta connection is adopted instead of the star. Mr. Taylor in his paper says that when we sum it all up, the operating risks in the delta are the same as in the star. That may or it may not be so, but still he is faced with this, that all the highest pressures have a delta connection, and as I say, this is the opposite to what might have been expected. With regard to the question of working at 50,000 or 100,000 volts, Mr. Trotter has very properly pointed out that in this country there will never be any necessity for working at 100,000 volts, or anything like it, for economical reasons. I remember reading some time ago a very important paper by an eminent engineer in the United States, who had under his control a large number of lines at 60,000 volts, and he gave it as his considered opinion that it was easier to operate lines at 60,000 volts than at 30,000 volts. The reason he gave was this. At 60,000 volts the working current is only half what it would be at 30,000 volts. The pressure surges in the line due to opening short circuits, etc., can be expressed approximately with regard to their magnitude as a function of the current flowing in the line. The consequence is that, working at 60,000 volts, it is quite possible that the maximum pressure which the insulators may be called upon to stand, and which consists of the surge pressure superposed on the working pressure, will be considerably less than the maximum pressure when working at 30,000 volts, because in the former case the currents are so much smaller. I would like to ask the authors of these papers whether this advantage of operation continues to hold when we jump from 50,000 volts up to 100,000 volts. It cannot be pretended, of course, that a pressure of 60,000 volts is at all necessary from an economical point of view for a 14-mile transmission, such as the example given in the paper, or that a pressure of 110,000 volts is necessary for a 50-mile transmission, and unless there is some great advantage in operating at these higher pressures it seems to me just possible that we may be going too far in that direction. Mr. Esson.

Mr. A. A. Campbell Swinton: Mr. Trotter has alluded to the fact that in this country these extremely high pressures are not very likely to have much application, but still this Institution has many members who may have to deal with transmission problems in Africa, India, Canada, and other places where the use of very high pressures may be economically sound. It is a question of some importance, therefore, what factor does really limit the pressures that can be used. Mr. Peck has mentioned the limiting factor of the insulators, which has been improved, and I have no doubt will be still further improved in the future. But the real limiting factor as regards the pressure that can be employed on overhead lines is the point at which the air breaks down. At this point we begin to lose power in what we used to call a brush discharge, but what has apparently now had the American name given to it of "corona discharge." I think "brush Mr. Swinton

Mr Swinton.

discharge" is a much shorter and probably better term, but anyway, that is what sets the limit as regards pressure. Diagram 13 in Messrs. Matthews and Wilkinson's paper is very instructive. It shows that for a conductor of a certain size, viz., ¼ in. in diameter, we can get up to about 120,000 volts with very little loss of this description, but between 110,000 and 120,000, and still more when we get up to 130,000, the curve takes a sharp bend and the loss increases rapidly. That, of course, is for this particular size of conductor only. With a conductor ½ in. in diameter no doubt this bend in the curve would take place at a very much higher voltage. There we have one way in which we can increase the pressure at which we can work. We can use larger wires, and, as is pointed out in one of the papers, by using aluminium instead of copper we can have a larger wire of the same weight and approximately of the same resistance. I do not know whether anybody has considered the question in regard to these high-tension overhead lines of going back to iron or steel wires, but I am not at all sure that that is not worth consideration. We could have very long spans; we would have great tensile strength, and we could then string the wires up very tight. Of course the resistance with steel wires would be much greater, but when we get to these very high voltages resistance becomes of decreasing importance. Any one who has worked with very high-tension currents is aware that there are several factors that have a great effect upon the point at which much energy begins to be lost by way of brush discharge. The condition of the surface of the wire has a large effect. If the surface is very smooth there is very much less tendency to brush discharge than if it is rough; and I should be glad to know from the authors of the papers whether there is any experience as to the losses due to brush discharges increasing with time, because I should expect that with the effect of the atmosphere on the wires this might very likely occur to a considerable extent. The loss might quite easily be doubled or trebled as the surfaces became rough and as little particles of carbon or other material formed upon them. Since the paper was read it occurred to me to try whether it was possible in any way to increase the pressures at which we could carry currents on overhead wires by slightly insulating them, so as to prevent brush discharges taking place. There are many insulating substances which have a much greater dielectric strength than air in the ordinary way, but that is only within limits. As a matter of fact, when we come to very thin films air has effectively a greater dielectric strength than any solid substance. This is due to the great difficulty experienced by electricity in emerging from a solid conductor into a gas, and the result is that it appears doubtful whether any thin coating of solid insulation applied to a conductor can have much effect in stopping brush discharge. Anyway, some experiments that I have tried point to this conclusion. If this is so, the only means by which we can hope to increase the allowable pressure is by increasing the size of the conductor, which should of course always be perfectly cylindrical, making it either of a light metal like aluminium,

or, if of copper, making it hollow. Care can also be taken to maintain a smooth surface. Mr Swinton.

Dr. M. KLOSS: The two papers now under discussion give much interesting and valuable information on high-voltage transmission lines. As pointed out by Messrs. Matthews and Wilkinson, there does not seem to be a great demand for such lines in the near future in this country; but in foreign countries there are a great number of lines already in operation, and no doubt many more will be installed. The authors of the two papers now before us confine their data and experience to American practice. It might, therefore, be of some interest to refer to the work and practice of Continental engineers. The Siemens-Schuckert Works, for instance, have installed high-voltage transmission lines at Munich, Kykkelsrud (Norway), Salto Bolarque (Spain), all working at 50,000 volts, and Molinar (Spain) for the Sociedad Hidro-electrica Espanola, at 70,000 volts. The distance is not very great in the first two cases, being of the order of about 30 miles, but in the case of the Molinar power scheme the energy is transmitted to Valencia and Alcoy, a distance of 50 miles; to Cartagena, over 100 miles; and to Madrid, over 150 miles. Besides the long-distance lines there seems to be on the Continent an ever increasing demand for the so-called "district power distribution schemes" similar to the Cleveland and Durham power scheme on the north-east coast. Such a scheme has, for instance, been successfully put into operation at Wiesmoor in North Germany. Moreover, the time will soon come when the first 110,000-volt scheme in Germany will be working. This is going to be installed at Lauchhammer and will supply electrical energy to various industrial works in the north of Saxony and south of Prussia. The transformers for this scheme are of 6,800-k.v.a. capacity. With reference to the high-voltage transmission lines themselves, Continental practice is in many points similar to the American, but in some respects also more or less different. The spans range from 400 to 650 ft. It is thought advisable to run up the mechanical stress in the line conductor to as high a value as is consistent with safety. In accordance with the V.D.E. Rules (that is, the rules laid down by the German Association of Electrical Engineers) a stress of 16 kg./mm.^{2} or 22,700 lbs. per square inch is permissible provided the limit of elasticity is 40 kg./mm.^{2} or 57,000 lbs. per square inch. This enables the sag to be kept relatively small and consequently reduces the required height of poles. If a line runs alongside a road or through a village a higher safety is required. The mechanical stress in the conductors is therefore to be kept at, say, half the value given above, that is, 8 kg./mm.^{2} or 11,400 lbs. per square inch. Moreover, in such cases as where greater safety is required, a short shunt wire is fixed to the conductor in front of and behind the insulator, so that, in case of the insulator breaking, the conductor cannot fall to the ground, but will rest on the cross-bar, thus grounding the line. In case of a conductor breaking between two poles, the grounding is accomplished by the wire touching a bracket attached to the pole and projecting about 4 to 5 ft. in the direction of the line, Dr. Kloss.

Dr. Kloss. Where the line crosses a railway, or telegraph or telephone lines, special safety devices are necessary. In accordance with the rules a wire net is to be provided round the line, or the conductors are to be tied to the poles by the so-called "treble suspension." The latter construction is given the preference. This design is carried out in the following way: To the main conductor are attached two pieces of wire of the same diameter and about 3 to 4 ft. long, and each of them is tied to a separate insulator, so that the line is attached to three independent insulators, each of which holds it with a factor of safety of 5. Besides this the conductor itself is only stressed to about 4 kg./mm.^{2}, representing a factor of safety of 10. At the crossing of a telephone line a grounded safety cable is also fixed below the high-tension conductors so as to prevent a telephone wire from touching the live conductors should it break.

With reference to the protection of the line against the influence of excess pressure and lightning, the Continental practice is rather different to the American, and even the various firms differ from one another in this respect. None of the lines which I have mentioned are provided with an overhead grounded cable, but special protecting apparatus is installed at both ends of the line, and for a long-distance line at some intermediate points as well. For instance, the 150-mile line from Molinar to Madrid is provided with 5 protection stations besides those at the ends. So far as the protecting gear itself is concerned, some firms use aluminium arresters or roller lightning arresters. In my opinion the latter type is likely to do more harm than good, in so far it is apt to produce high-frequency oscillations when acting, thus introducing a new source of danger. The aluminium arresters have the disadvantage of requiring daily attention for forming the oxide film on the electrodes. In my opinion the best lightning arrester is the well-known horn type in connection with a limiting resistance, which in cases of infrequent operation is wound on enamelled cylinders. In the case of frequent operation the resistance wire is submerged under oil. For getting rid of static charges water-jet earthing devices are used or choking coils. In order to protect power apparatus, such as machines or transformers, against excess voltage surges, choking coils are used, because it seems impossible effectively to insulate the end turns of the apparatus against the enormous rise of pressure between turns which may occur in case of surges. So far as such surges are due to the switching in or out of large power apparatus, they can be greatly reduced by the use of a special safety switch, provided with a set of auxiliary contacts which cut in a limiting resistance step just before the switch is finally closed.

Mr. Taylor mentions the voltage regulation as representing some difficulties. In this respect we might use step-up transformers or induction regulators which may be operated either by hand or automatically. Such apparatus works very satisfactorily and is quite reliable in its action. A very interesting point mentioned in both papers is the "corona" effect. After all the difficulties in connection with the insu-

lators have been successfully overcome so that high voltages over 100,000 volts are now quite practicable, the corona effect seems to set a limit which cannot be surmounted, because it is due to a physical property of the atmosphere on which we have no controlling influence as in the case of manufactured materials. Since the corona effect increases with decreasing diameter of wire, aluminium wire seems to offer a great advantage over the copper as mentioned by Mr. Taylor. Messrs. Matthews and Wilkinson give a very instructive curve of the increase of corona loss with increase of voltage for a wire of $\frac{1}{4}$ in. diameter. The curve does not represent a uniform law, but obviously follows one law in its lower range and then changes almost suddenly to conform to a different law. It seems to me that the flat portion of the curve up to about 115,000 volts may not be due to corona effect at all, but may rather represent the watt loss of the charging current. So long as the electric field keeps below a certain density the air surrounding the conductor acts as an insulating medium. However, at a certain critical value of field density the air loses its insulating properties and becomes a conductor, so that now a current passes from the wire into the surrounding air and back to the other conductor or conductors. It would be very interesting if the authors could show similar curves for different sizes of wires, so that a curve could be plotted giving the relation between the critical voltage and the diameter of wire. Since the size of wire limits the current due to current density and at the same time limits the voltage due to field density producing the corona effect, the maximum power which can be transmitted through a given diameter of wire is also limited, and consequently there must be a definite relation as well between the voltage and the permissible power to be transmitted. It would be of great interest if the authors could give us their opinion on this point. Perhaps one of the most valuable suggestions made by the authors is that a line should be operated at a voltage only slightly below the critical point. Under normal working conditions no corona loss will occur, but as soon as the voltage rises, due to lightning or surges in the system, the oscillating energy will be dissipated automatically by the corona effect. It is quite possible that if this peculiar phenomenon were made use of properly in the design of the lines great expense might be saved by enabling the number of protecting apparatus to be reduced to a minimum. This would mean compelling an evil to effect some good, and that should always be the aim of our profession. Dr. Kloss.

Mr. B. M. JENKIN: With regard to the pressure that we are likely to use, Mr. Trotter has suggested that we are not likely to work at high pressures in this country because by increasing the pressure we only reduce the size of the wire, and therefore the saving is only in the cost of the conductor. I think there is another, and perhaps more useful, way in which the point might be looked at, and that is to consider the power that can be transmitted by a given line. If the poles have been put up and the conductors and insulators, then if the pressure be doubled twice as much power can be transmitted by this line by merely increasing Mr. Jenkin.

Mr. Jenkin. the insulators. With the higher pressure the cost of the line per kilowatt transmitted is practically reduced to half what it was with the lower pressure.

ADJOURNED DISCUSSION, FEBRUARY 23, 1911.

Mr. Sparks. Mr. C. P. SPARKS: The papers before us deal with a subject with which we have little, if any, experience in this country, the primary reason being, in my opinion, that the amount of power we transmit is as a rule comparatively small, owing to the absence in this country of sources of water-power, and to the distribution and number of our coal-fields. As far as I am aware, the maximum power that is ordinarily transmitted here is of the order of 4,000 to 5,000 k.w. per feeder. In the papers before us the actual power transmitted per feeder is not given, but the maximum must be in the order of some 20,000 to 25,000 k.w. per feeder. One of the speakers on the last occasion drew attention to the difficulties of transmitting any large power with overhead lines unless high pressures were used, in view of the remarks of a previous speaker who suggested that the future limit of pressure in this country would be of the order of 20,000 volts. I am of the opinion that when the time comes for these overhead transmissions we shall be forced to much higher pressures than 20,000 volts. I think 40,000 volts may be taken as quite a minimum, the reason being that it is not possible to handle an overhead conductor of more than a limited size, and if the pressure is limited to 20,000 volts it is not possible to transmit any large amount of energy without using a large number of feeders. Therefore if individual schemes are big our transmission pressures must be above 20,000 volts. When once these extra high pressures are used there appears no reason why we should be limited to such a pressure as that suggested, namely, 20,000 volts, because the difficulties are already so great when we deal with a pressure of that kind that the additional difficulty of operating at twice or three times the pressure, *i.e.*, 60,000 volts, are not commensurate with the additional capital expense in insulators and sub-station apparatus. I am therefore of opinion that we shall operate in this country with very much higher pressures, the limit at the present moment being the 20,000 volts used in the Tyne district. One point about which I should like to have heard more is the question of continuity of service, which is touched upon by both of the authors. From the commercial point of view the first essential is continuity of service. We have it on record that the line is the most unreliable part of the whole system, compared with the generating station and the substations. In the papers before us little is said as to methods of protection. The methods of operation indicated are extremely simple, and appear to be limited to cutting off a whole circuit and then transferring the load to a second circuit, which means that the supply to consumers who are taking anything from 15,000 to 25,000 k.w. may be cut off for an indefinite period. The possibility of such an interrup-

tor is so serious a matter from the point of view of users in this country, that before any big system of overhead transmission is projected here the questions dealing with safeguards such as we use with underground cables are bound to be considered. Mr. Matthews suggests that to secure reliability there should be two separate pole lines, and Mr. Taylor emphasises the desirability, in future developments, of splitting the main lines. As I understand the paper, by splitting the main lines the author means that instead of transmitting 20,000 k.w. on one set of three wires he will transmit 10,000 k.w. or less, that is to say, he will come more into line with the conditions of operation existing here. The next matter that I should like to refer to is the limiting pressure of transmission. I think Mr. Matthews suggests that 200,000 volts is considered to be within the region of practicability. In a recent paper by Mr. Faccioli particulars are given of the actual loss on some of these transmission lines.* The corona and insulator losses were separately determined on the transmission line from the Shoshone station, and it was there found that, operating at 95 kilovolts, the corona and insulator losses were under 600 k.w., and that when the pressure was raised to 105 kilovolts these losses had risen to over 1,600 k.w. From these figures it appears that until some method of preparing the surface of the conductor, insulating the conductor or enlarging its surface, is found, anything like 200,000 volts is outside practical limits. Mr. Sparks.

A most interesting point is brought out by Messrs. Matthews and Wilkinson on page 572 of the power of a line to discharge the excess energy if slightly raised above the operating pressure. "Any induced surges or other high-tension phenomena are thus automatically dissipated in the form of corona discharge between the wires, and the line acts as its own safety valve." I have not considered that point before, but it appears to be a most valuable adjunct in solving a great difficulty in an overhead transmission system. If the line is operated just below the critical point, then when the line becomes charged by either a surge or when struck by lightning, and the line possesses the power of radiating or breaking down and discharging a large amount of energy for every extra 10,000 or 15,000 volts added to the line, it seems we have here a most practical safety valve. Mr. Taylor touches on the question of direct-current transmission with overhead lines. This, again, is a very interesting point, but he only says that "probably the day is near at hand" in regard to its adoption. With regard to the overhead line itself, direct current is of course a solution, but the difficulty of the sub-station apparatus and of the generating apparatus is so great that I do not think he is justified in suggesting that the use of high-pressure direct current is probably near at hand. I think it is as far distant now as it was five years ago. The third point I wish to speak on is "earthing." Both of the papers tell us that the general practice is to have an earthed line suspended overhead, which, in addition to providing an earth, acts as a

* *Proceedings of the American Institute of Electrical Engineers*, vol. 30, p. 99, 1911.

Mr. Sparks. support for the steel towers. But neither paper tells us how we are to secure the safe discharge of these towers. One author suggests that the legs of the tower should project through the concrete for a certain distance into the soil. Now subsoils vary tremendously in resistance, and some much more careful method of earthing than that suggested is necessary for the general safety of the public (although the public may be scattered in these transmission districts) and also for the safety of the people whose duty it is to maintain the lines. With regard to insulator tests, Mr. Matthews tells us that a single insulator, dry, stood a test of 90,000 volts. I understand the paper to read that when six of these insulators were in series they would stand a test, dry, of 360,000 volts, or 60,000 volts per insulator, and when wet of 270,000 volts. The next point I wish to mention is sub-station costs. Messrs. Matthews and Wilkinson give us a curve, No. 7, showing the approximate cost per kilowatt with 2,250 k.w. static sub-stations. The curve gives points at 10,000 and 20,000 volts, about which we know something here. The authors suggest that the cost of the static sub-stations at the lower limit of 10,000 volts is £3 a kilowatt. I should like further information as to what is included in the cost of the sub-station, because at present prices, if we divide the figures at the lower pressures by 2, there is still a large margin that contractors here would cordially welcome. The last point to which I wish to refer is that of the price of power. The figures given clearly bring out that the commercial cost of electric power in this country, when using coal for generation, still allows manufacturers in the old country to get a good margin on their manufacturing costs—that is to say, although this so-called cheap power from water is a great boon to people who cannot get other power, it is not relatively cheaper, when distributed, than we are able to supply the manufacturers with in this country.

Mr. Woodhouse. Mr. W. B. WOODHOUSE: There is one matter in both papers that I am sorry to see not touched upon, and that is the question of wayleaves. In this country we have already several hundred miles of overhead high-pressure transmission lines, and the mileage is very rapidly increasing, but we are unfortunately situated compared with other countries as to the conditions under which these lines are put up. We have to obtain wayleaves to erect poles and run wires with the consent of the landowners and the tenants. That consent may be refused absolutely, or it may be given upon the most onerous terms, and, what is perhaps more dangerous still for the continuity of public supply, the consent may be given for but a very few years. In most of the Continental countries, and I understand in America, legal machinery exists for obtaining compulsory wayleaves for public supply. No landowner is allowed to be unreasonable enough to prevent public supply overhead lines being taken through his property by a reasonable route. He must give a good reason for dissenting, and if he cannot it goes through at a reasonable price. In this country we are at the mercy of the numerous landowners, and as time goes on I suppose there will be still more trouble in that respect. It does seem to me a matter which, if

we are to get the cheap general power supply that we all hope for, the industry should consider as an important one. I venture to suggest it as a matter that the Institution itself might treat as being vital to the industry. The laws as to easements work quite satisfactorily in other countries, and I think the subject only needs to be taken up here in this country for the present state of things to be remedied. Public power supply is a very great blessing in all industrial parts of the country. The smoke nuisance is very much more than a nuisance—it is a serious menace to health. Public officers of health all over the country are raising their voices against it, and it seems to me that if we can show the public a solution they will be on our side. We have another difficulty to face with overhead lines, and that is the restrictions of the Electric Lighting Acts. Every local authority can, without reason, refuse an overhead line being put up in their district. Overhead lines may be run on private property and never cross a public road, and yet a local authority may say " No." In my own experience I have known cases of local authorities refusing their consent without reason, sometimes from very obscure motives. On those two points I think other countries in which power supply has been developed are very much better off than we are, and if an improvement in those respects could be made in this country I am sure it would tend to a very rapid development of the use of such overhead lines as are described in the papers. Mr. Woodhouse.

Mr. E. J. Fox: The two points that I wish to touch on quite briefly to-night are matters of detail in regard to the two subjects contained in the papers. The first one, which Mr. Trotter dealt with on the last occasion, is the question of wood poles *versus* steel poles. I do not think there is much more to be said on that subject. The general consensus of opinion seems to be that 10 years is the fair average life for wooden poles and 30 years for steel poles. I understand, however, that in many quarters it is considered that wood poles, if properly treated, may be considered to have a life of perhaps 20 to 30 years, which brings up their life to the life of steel poles. The determining factor is, however, the question of the relative first cost of the one as against the other. Wood is increasing in price very much, with the result that steel poles are available nearly at the cost of wooden poles. Mr. Trotter placed the life of wooden poles at about the life of steel poles, but as the Board of Trade stipulate for a factor of safety of 10 in the case of wood and 6 in the case of steel, this is another factor which militates in favour of steel. Mr. Fox.

Mr. TROTTER: May I correct you in that statement? I do not think I said that the life of a wooden pole was equal to that of a steel pole. I should put it at five times the life of a steel pole. Mr. Trotter.

Mr. Fox: This view is certainly opposed to general opinion on the subject. My second point deals with the question of the design of the towers. I am rather surprised that in Messrs. Matthews and Wilkinson's paper, which is a summary of what has been done in the United States, the design of towers is confined to sectional towers—in other Mr. Fox.

Mr. Fox. words, towers built up of channels, angles, tees, and so on. I think I am right in saying that the design of tubular towers is receiving consideration at the present time to a greater extent than the design of sectional towers, chiefly on the grounds of weight, but also for reasons of first cost. The principal members of these towers are designed as compression members, and when we come to compare the strength of steel of a given quality, say steel of 26 to 28 tons tensile strength, we shall get greater strength from the tubular design than from the sectional design. It may be of interest to know that the installation in Cornwall referred to by Mr. Trotter on the last occasion, where transmission lines are being laid down, that the towers are entirely built of tubular section. The following comparison is of interest in this connection: Roughly speaking, a tubular tower will be about half the weight of a tower built up of sectional iron, but in actual figures the comparison is as follows: Angle iron weighing 22 lbs. per foot will have the same moment of inertia—*i.e.*, the same strength from the point of view of these towers—as a tube weighing 8 lbs. per foot; that is, 22 lbs. *versus* 8. If we take iron of tee section we have 16¼ lbs. per foot for the tee section *versus* 7 lbs. per foot for the tubular section. In channel iron section we have 16 lbs. per foot for the channel section *versus* 6 lbs. per foot for the tubular section; and finally in an H-beam section you have 12 lbs. per foot for the H-beam *versus* 4 lbs. per foot for the tubular section. Apart from the question of weight, which of course means cost, the majority of these installations are abroad. Although in this country there is a limited field for transmission lines, the majority of these installations are abroad, and there the question of transport over heavy country, and the question of facility of erection weigh very much in favour of the design which is the lightest. So far as erection is concerned, towers of the design to which I am referring can be erected at the rate of three per day for the flexible towers or intermediate towers, and at the rate of one per day for the straining towers. I think this is quicker than it is possible for the erection to be carried out with towers of the design described in the papers, and which we saw on the screen on the last occasion.

Mr. Jacob. Mr. A. Jacob: I have looked through the papers under discussion and consider that they strikingly illustrate what might be done in this country in the distribution of power on the lines indicated by Mr. Ferranti in his Presidential address. Mr. Taylor's paper is a specially interesting contribution to what has already been written on this subject, and the data and practical information he gives will be valuable to engineers concerned in this problem. It is a curious fact that neither author deals with the important part which aluminium now plays in power transmission schemes, nor do they give any details of the 110,000-volts system recently put into operation by the Hydro-Electric Power Commission of Ontario, upon which aluminium has been employed throughout. Upon this system the total length of line installed is 283 miles, the average pole spacing 525 ft., the height of towers 65¼ ft., and on the complete scheme, including the 13,200-volt

distribution system, over 2,000 tons of aluminium will be employed. Mr. Jacob. The chief and most important differences in the design of transmission lines in this country and in U.S.A. and Canada is in the safety factors adopted, the factor required in England being at least twice that upon which Canadian lines are erected, and this notwithstanding the fact that much more adverse weather conditions are met with in Canada than are ever experienced in England. Under these conditions the capital investment required, and the difficulty in obtaining wayleaves, places serious limitations upon the field for long-distance power transmission in England. In calculating the sag to be allowed upon a copper or aluminium cable at any given temperature so that it shall not be loaded beyond a given point under the most adverse conditions of wind and temperature, the formula commonly used in England takes no account of elasticity, and the stresses so calculated are far greater than those met with in actual practice, owing to the material being elastic. This difference may be as high as 300 or 400 per cent., and will result in the whole line being constructed at quite unnecessarily heavy expense. The points chiefly raised against the adoption of aluminium are the difficulties in jointing it, and that it corrodes more rapidly than copper, more especially when erected near the sea coast. The joint now commonly adopted on long-distance transmission work, not alone on aluminium, but also upon copper lines, is of the McIntyre torsion sleeve type, and it has proved to be quite satisfactory in practical operation. Upon some of the earlier lines solid aluminium wire with copper binders and clamps of metals other than aluminium were employed, with the result that trouble from galvanic action ensued. In general, therefore, it is well to avoid mechanical or electrical contact between aluminium and other metals, but where joints of this nature are necessary, provided they are efficiently protected from moisture, no trouble need be anticipated. The tensile strength of pure aluminium can be very materially increased by alloying it with copper and other metals, but this increase is more than counterbalanced by more rapid deterioration and a proportionate increase in the resistance of the alloy wire. Aluminium has now been in operation for many years upon over 70 important transmission schemes, and on the whole it has withstood atmospheric conditions at least as well as copper. I have placed on the table a sample of pure aluminium wire cut out of a line erected in an exposed position on the sea coast; it has been in operation for over 8 years and shows little or no signs of deterioration. Such difficulties as have been experienced in the past in the employment of aluminium have in my opinion been mainly due to lack of experience in the handling and erection of a new metal and to the use of low-grade metal for the purpose.

In conclusion, I would point out that in the typical case taken by Mr. Taylor on page 541, the cost of the conductor in aluminium would be £35,600, or £18,600 less than he calculates the cost for copper, showing a saving of about 35 per cent. on the cost of the conductor.

Mr. Jacob. While making full allowance for the increased area of the aluminium wire, I cannot see that it would be economical to employ copper upon such a line. By the courtesy of the British Insulated and Helsby Cables, Ltd., I am in a position to place upon the screen some views of typical aluminium lines erected in this country :—

Slide No. 1.—Terminal pole and general view of 1·4 sq. in. aluminium line erected for Newton Chambers & Co. Length of line, 1·2 miles.

Slide No. 2.—General view of 1·4 sq. in. aluminium line erected for Newton Chambers & Co., showing guarding and straight joints. Also showing where line changes from H to single poles. Length of line, 1·2 miles.

Slide No. 3.—General view of 1·4 sq. in. aluminium line erected for Newton Chambers & Co., showing cradle guarding over road and straight joints. Length of line, 1·2 miles.

Slide No. 4.—Shows method of jointing 1·4 sq. in. aluminium line erected for Newton Chambers & Co. This is one of the actual joints shown on slides Nos. 2 and 3.

Slides No. 5 *and* 6.—Are two views of 3,000-volt, 3-phase, 0·25 sq. in. aluminium line 3·1 miles long, erected for the Weardale Steel and Iron Co., for connecting together their two power stations at Wyngate and Thornley.

Slides No. 7, 8, 9, *and* 10.—Are pole views of a complete distribution system carried out at Ystradgynlais. The lower wires on Nos. 7, 9, and 10 are No. 14 S.W.G. The other sizes are 7/0·159, 3/0·237, 3/0·144, 3/0·174, 3/0·096, 3/0·120, 3/0·122, 1/0·083, (14 S.W.G., 1/0·103 (12 S.W.G.).

Communicated : The tests referred to by Mr. A. J. Stubbs (see p. 620) as being carried out by the Post Office upon aluminium wires of small gauge have in my opinion little bearing upon present-day aluminium practice. As Mr. Stubbs points out, these tests were carried out ten years ago, and at that period little was known of the properties of aluminium or the methods of converting it into wire or strand. View Nos. 7, 9, and 10, which I placed on the screen, illustrated some aluminium lines in South Wales, upon which the conductors are No. 14 S.W.G., and these lines have now been in satisfactory operation in a position where severe weather conditions are met with for over two years. I have no doubt that were these tests now repeated very different results would be obtained.

Mr. Greene. Mr. C. J. GREENE : So many points have been touched on that it leaves very few still to be considered, but at the same time there are several points of detail which are of interest in connection with the actual erection of these lines, and which are, I think, not sufficiently prominent in the papers. I therefore hope the authors will give us a little further information upon them. In the first place, in these long spans it would be interesting to know whether the factor of safety

on the conductors is obtained by working with a dynamometer and getting the actual tension in the conductors, or whether it is obtained by in any way measuring the sag. There is a point in measuring the stress in these conductors by dynamometers which is very often overlooked. Nearly all tables which are compiled give the variation for temperature, but none of them allow any variation for wind pressure. If we erect a line, say, having a factor of safety of 5 on a calm day we shall not have a factor of safety of 5 in that line when there is a wind blowing. The consequence is there must be some table which allows for this varying wind pressure. If we erect a line on a day when there is a flat calm, with no wind pressure, the tension to which we pull up the conductors must be very considerably less than one-fifth of the breaking strain of the line. There is a difficulty in this, because if we are going to work actually to any table we must know on the particular day on which we are erecting the line, not only the wind pressure, but the relative direction of the wind pressure to the line itself; and it would be interesting to know what the American practice is in this particular case. The next point to which I wish to direct attention is the jointing of conductors in between spans. I was very interested to see the clamp joint shown on the screen by Mr. Jacob. So far as the McIntyre joint goes, I believe it makes a thoroughly sound working joint, but it is a joint that does not give the same strength as the strength of the line itself, and in this country when lines have to be pulled up to a definite stress this leads to complications. Various tests have been made on these McIntyre joints by actually putting them in a testing machine and pulling them apart, and the over-all strength of these joints is in the nature of 60 per cent. of the strength of the line itself. If we are going to erect a line with a given factor of safety it means that if we insert one of these McIntyre joints in that particular span we shall get a very much lower factor of safety than 5. I do not say that this absolutely precludes the use of this type of joint, but still the fact remains, and if we are going to get the same factor of safety in the span where the joint occurs we must erect it with a much greater sag. It is possible that this clamp joint which was shown on the screen may have a greater mechanical factor of safety than 60 per cent. of the line, and it would be of interest to know what the actual over-all strength of that joint was. These remarks do not apply particularly to aluminium, because I think any joints of this nature, whether made of copper or aluminium, must of necessity have very much less strength than the line itself. I believe it is the practice of the Post Office and the National Telephone Company on their smaller wires to make an ordinary Britannia joint, and here again it would be interesting to know whether any of these Britannia joints have ever been actually put in a testing machine and pulled apart, and if so what is the strength of the joint compared with the strength of the line. Mr. Greene.

The next point to which I wish to refer is the question of conductors swinging in the wind. I notice the authors said that these

Mr. Greene. conductors all swing together. I believe that is true of copper, but I am not at all certain that it is true of aluminium. The aluminium conductors are so light that when a sudden gust of wind strikes one of these spans the conductors suddenly fly out from the sudden gust, and if there is any small difference in the tautness with which the individual wires are pulled up, or if there is a large joint in that particular span, I am strongly of the opinion that these conductors would swing out of phase. Further, with aluminium conductors there is the possibility of their breaking at the positions where they are bound to the insulators. It would seem possible that the swinging of these conductors in high winds would cause local crystallisation or deterioration at the exact point where they are gripped or bound. Information on this point would be exceedingly valuable.

The third point to which I wish to refer is the question of poles. I do not quite know what the standard specification would be in America so far as the factor of safety goes. Would this cover the breaking of one or more wires on either side of the pole? In Figs. 13, 14, and 15 the poles appear to be bolted down to a bed of concrete. I am not quite certain whether this is so, or as to whether that is a principle generally adopted in America. I should be glad to know what the standard practice is in connection with bolting down or fastening these large iron poles. So far as wooden poles go in this country, many more lines have been erected with wooden poles than with steel or iron poles. I think that up to spans of about 100 yards—80-yard spans are about the largest we have in this country—the cost of the wooden pole compares very favourably with the steel pole; in fact, we may take it that up to 100 yards the cost of wooden poles is less than that of steel poles; but on spans of about 100 yards I think we reach the turning point. It may be of interest to state that large tripod poles have been erected in this country in wood up to a total over-all height of about 102 ft. These poles carry six conductors, the sectional area being about 0·1 sq. in. These were poles built up, and naturally not all in one piece. With reference to the insulators, I am not quite certain what the practice is in America as to the specification for flashing-over under rain, but insulators of any type when subjected to heavy rain have their arcing distances reduced to such an extent that I think, from the point of view of continuity of service, it is a most important point that the factor of safety given in the specification for flashing-over should assume the worst possible conditions; and under these worst possible conditions I think a sudden rise of voltage must be assumed to take place, otherwise there will be a shut-down on the line. On page 536 of Mr. Taylor's paper the relative interruption on lines having the pin type of insulator and the suspension type of insulator is referred to. It would be interesting to know, first, how many insulators there were on each line, and, secondly, how many breakdowns they had on each line, that is to say, the actual figures rather than the percentage figures. A detail which is not clearly shown in the photographs on page 536 of Mr. Taylor's paper of an intermediate pole,

or an anchor pole, is the method of making the electrical connection between the wires coming from each direction. Mr. Greene.

Mr. E. H. RAYNER: Taking Mr. Taylor's paper first, there are various points in connection with it which seem to require further explanation. On page 540 there is a very important matter referred to which the other speakers in the course of the discussion have not touched upon, and that is the apparent kilowatts required to keep a very high-voltage line charged. The author mentions a line of 135,000 volts, which we may take as a maximum for the moment, and 125 miles long, and that line requires a machine of a normal output of 11,000 k.v.a. simply to keep it charged, giving no power at the other end. Running a machine of a capacity of 11,000 k.v.a., even at a low-power factor, corresponds to a good-sized steady load; and this is a matter of very great importance in considering these long lines of very high voltage for alternating current, especially when coal is to be used as the source of power. If we have any machine of less power than 5,000 or 10,000 k.w. we shall never be able to run it alone; we must have 10,000 or 20,000-k.w. machines, or have machines running in parallel which have that capacity in order to actually keep the line charged. If we have a machine of 500 k.w. it will simply burn out. Then on page 544 Mr. Taylor discusses the question of star and delta connections on the high-voltage side of the transformer. There is one little advantage which may arise in future in the use of the star connection, and that is that only one high-voltage terminal on the transformer is needed. The terminal question on high-voltage transformers of 100,000 volts is a very important one and very expensive. If we go straight away to a star-connected system we practically earth the other pole of the high-voltage winding, and we need only have one terminal which has to have this very high insulation. That is one item which may save a considerable amount of money in high-tension plant. In Messrs. Matthews and Wilkinson's paper there are one or two points in regard to which a little further information would be useful. They deal, for instance, with the B. and S. wire gauge, but do not give sizes in inches as well, which would be more useful. Then on page 574 the authors mention the wind velocity, and state that the usual allowance in the United States is ½ in. thickness of ice all round the wire, with a 65 mile per hour wind velocity occurring at the same time. But the authors give no indication of the relation joining the miles per hour and the horizontal force per foot run of the wire, so that we can get no further in our calculations. The value of this factor, whether it is taken as depending on the square of the velocity of the wind or not, will be useful, especially if reference to experimental data can be given. The authors mention also that the overhead ground wire should be earthed with great care. Do they mean that a special ground wire is run down from the top of each tower, or can the tower legs be trusted to make a sufficient earth connection? It has been suggested that special cross-pieces should be put, I think, in the earth, or that the legs should be run through the concrete, but the statement that the overhead ground wire should Mr. Rayner.

Mr Rayner. be earthed with great care needs a little more amplification. The authors deal with the question of very high voltages, and express opinions as to what pressures we may reach in the future. My personal opinion is that 20,000 volts is a very small voltage, and if we look at page 578 of the paper we can see one reason. The authors there give the cost per mile of transmission lines for various voltages. If we look at the table that is given, we find that the cost per mile of a 50,000-volt system is £462, and if we double the voltage and make it 100,000-volts, the price comes to only £502. In other words, doubling the voltage and doubling the carrying capacity of the line only increases the capital cost 8·5 per cent. That in itself is a great argument for running at the very highest voltage we possibly can. There is another question which arises in connection with the corona, and that is that it may be necessary, in future, in order to insure continuity of service at these very high voltages, for the lines to be run at the breakdown point of the air. As Mr. Sparks mentioned, it seems to be a safety valve of the greatest importance. I think it is more than that. I think in time it will compel engineers to run at this "overflow" point, because if we work at 20,000 volts the lightning is very much more dangerous than if we run at 100,000 volts, and it may compel us to run at the higher pressure if experience confirms this immunity from lightning troubles. That is only an idea of mine. The insulator itself has not been mentioned by many people, and I thought perhaps a little experience which I have had with regard to some insulators might be of interest, as the trouble may have occurred on other lines. These insulators were used on the Mussoorie electric system in India under exceedingly trying conditions of rainfall. The system worked at the comparatively low voltage of 6,000 three-phase, star to earth, 45 amperes, and line wires of No. 7 S.W.G. The system is not a large one, but the insulators have given a great deal of trouble in the rainy season, when the rainfall is exceedingly heavy. The rainfall in the district is about 140 in. in three months, and as much as 20 in. have fallen in 24 hours and 9 in. in 3 hours. The latter is about as large a quantity as we have in three months in England. I have placed on the table one of the insulators which has been sent to us to test. The engineers have had considerable trouble through the insulators breaking off at the neck. The wire is tied at the neck, and the engineers thought that an arc started from the wire at the neck, owing to the action of the heavy rain, and went over the surface of the insulator and then down to the pin and cross-arm, which is 3 in. from the insulator. They consequently requested that tests should be carried out up to 20,000 volts, under conditions simulating a very heavy rain. On trial this was found to be quite out of the question. Though standing 50,000 volts dry, the tests showed traces of leakage at 6,000 volts when wet, and at 15,000 volts there was arcing along the dripping water. As the voltage to earth was 3,000 the conditions seemed to be probably safe from this point of view, and another cause was looked for. It was noticed that the insulators were not glazed along the bottom edge, and it seemed possible that the

porcelain might become water-logged. Some were therefore put in an oven to dry out, and others had the central hole partly filled with water. They were then subjected to a high voltage and the conditions of the two sets reversed. There was no doubt about the result. Those which had been dried would stand 50,000 volts and then arced to the pin without damage, while the soaked ones glowed all round the neck and over the groove in the top at 25,000 volts, and became quite hot in less than a minute. No doubt the water causes a high-resistance circuit which generates a considerable amount of heat, and the glaze is finally broken through. The insulators have been used, as I understand, with the line wire tied to the neck only. This accounts for their failing at this point. From the experiments it seems likely that more trouble would be caused if the top groove were employed, as the porcelain seems to be generally thinner at this point, and failure has generally taken place at the top after glowing more there than at the neck when conductors were fixed in both places. It is thus important to glaze all over, even the screw-hole. Mr. Rayner.

Mr. H. BRAZIL: The few remarks I have to make refer to the protection of the transmission line from electrical disturbances. The apparatus may, I think, be divided into three classes: the first dealing with surges, of which we have examples in the horns with resistance in series, the horns with aluminium cells in series, and the multi-gap with resistance in series. The second, dealing with slowly accumulating charges, takes the form of very high resistances passing very small currents continuously to earth, and as examples we have the water-jet arrester and the carbon-powder resistance. The third is that dealing with direct lightning strokes, and here we have as examples the ground wire and also widely-set arrester horns with or without resistance in the circuit. Dealing first with surges, Mr. Taylor speaks very well of the aluminium cell, but he does not give any details of the actual working. Although the cell is called electrolytic, it is dependent for its sparking voltage upon the arrester horn. It also depends upon the arrester horn for the putting out of the arc. I should like Mr. Taylor to tell us at what percentage above the normal voltage of the supply system he sets the arrester horn which is in circuit with the cells, as it is a matter of some importance in determining what protection is afforded to the line; and, secondly, what current flows to earth at the moment the discharge occurs. On the latter point I should like to call attention to the statement at the bottom of page 512, where Mr. Taylor says, "The effect on the line caused by a flash-over of the lightning arresters may cause a heavy disturbance on the whole system." I do not exactly gather why it should cause a disturbance. Why is a disturbance necessary? Does it not point to the fact that the particular arresters used passed too much current? It would seem that any arrester which is effective and is well designed should not by its action produce surges on the system. I have had no experience with 60,000 volts, but with 10,000, volts using horns and resistances, I have records of hundreds of dis- Mr. Brazil.

Mr. Brazil. charges, and with the exception of where water resistances, which have since been replaced, have broken down no disturbance has been caused on the system by the working of the arresters. Another point with regard to these aluminium arresters which has been already dealt with is that they must be charged once a day in order to keep the electrolytic film in working order. Further, I am informed that the electrolyte itself is by no means reliable; it is difficult to be sure that it always remains in the same condition. This reminds me of a little jest of Mr. Patchell's at a meeting of the Institution a year or two ago. He said that in Italy they waited until they saw the storm approaching before turning on the water to the water-jet arresters. One pictures to oneself the man in the watch-tower looking out for the storm, the telephone message to the switchboard, and the rush of the switchboard attendant to the water valve to turn it on before the station is destroyed. That may be magnificent, but it is not electrical engineering. I quite admit that it is possible for one to foresee a storm and to make provision, but I defy any one to see a surge approaching. The point I wish to emphasise is that apparatus of this kind must be ready at all times to deal with any conditions that may arise, and I therefore think the aluminium cell cannot be altogether satisfactory if it has to be charged once a day, nor if the electrolyte is unreliable. I was interested at the last meeting to hear Mr. Peck, who some two or three years ago was a staunch adherent of the aluminium cell and brought it forward as being the solution of the lightning arrester problem, now rather backs away from it. He admits the disadvantage of having to charge it once a day, and at the last meeting he brought forward a substitute which, if you analyse it, comes to nothing more nor less than a horn arrester with a resistance, which was in operation a long while before the aluminium cell appeared. Coming to the second division—slowly accumulating charges—I should be glad if the author will tell us what current is necessary to flow to earth in order to prevent an accumulation of potential. I have had some unhappy experiences, which Mr. Patchell will substantiate, with water resistances, and it makes one fight shy of any apparatus which involves the use of a liquid. The disadvantage of the water-jet arrester is that there must be a constant supply of water under pressure, which in many cases is impossible. Secondly, the variation in the resistance of the water owing to impurities getting into it is an important matter, and also the variation in size of the jet. This point was mentioned in a paper read last year by Mr. Clayton, who said that it was never possible to tell what currents one was going to get in these water jets owing to the variation in the resistance of the water. I venture to suggest that the carbon-powder resistances described during the discussion on Mr. Clayton's paper, one of which I have had working with one-tenth of an ampere on a 10,000-volt circuit for some weeks without any alteration whatever, is a much more reliable apparatus. In connection with the third division—the direct lightning strokes—the ground wire has been brought forward as a

solution of this difficulty, but in the course of the discussion one speaker has said that he would rather be without it. Opinion seems to be very divided as to whether it is useful or not. I should say it was useful under certain circumstances, but clearly if the overhead line gets struck by lightning the ground wire is useless, because it cannot discharge the overhead line; and besides that it is very expensive. Widely-set horns, say with about an inch gap, connected between the line and earth, with or without resistance in circuit, seem to be a solution to some extent. As to how far they are a solution I cannot say, but I should be glad if Mr. Taylor would tell us. The question of putting resistances in circuit with the horn is a rather interesting one. If a resistance is put in, it should be non-inductive and capable of taking a very heavy load. I think a small resistance is very good, because when lightning strikes the line it prevents a very heavy current flowing from line to earth. On this point I should like to put before the meeting an interesting experience to which my attention has been drawn; it is not in my personal experience, it is only what has been told me. On an overhead line in this country it was found that when arrester horns were connected to the overhead line, and the other side of the horn was connected direct to earth, flashing-over occurred fairly frequently, especially during the evenings and at night; but immediately a resistance was put in circuit with the horns (I may mention that the arrester horns were set at a wide gap in the first instance) they could set the gap at a very much smaller figure, and they did not get discharges. I do not profess to explain this, but should be glad if Mr. Taylor or any other member could put forward a solution. I should like to suggest that we follow rather too much like sheep on this question of the protection of transmission lines. I have known cases where thirty feeders were connected on to a common bus-bar, each feeder being provided with a lightning arrester. The majority of those thirty arresters were not working; they were there for show, because either the resistances were broken down, or else the gaps were set so impossibly high that they could never spark across. If a few properly working arresters were placed on the bus-bars, we should have much better protection than with all those thirty, connected one to each feeder. Mr. Brazil.

Mr. B. M. JENKIN: I do not know that I am in order in speaking a second time, as I occupied a short space of time on the last occasion, but I would like to emphasise what Mr. Sparks has said, for the thing that really determines the voltage to be used on a given transmission line is not its height, but the amount of power it has to transmit. In America the tendency has been to raise the voltage. They speak of transmitting 50,000 k.w. on a one-pole line, and to do that they have to use 100,000 volts. In this country we have not got long distances, but we may have the other and perhaps greater difficulty to contend with of obtaining wayleaves, and that will, I think, make us use these high voltages. It is difficult enough to get wayleaves for a one-pole line, and when we have to transmit any Mr. Jenkin.

Mr. Jenkin. amount of power we must take it by that single-pole line, and not have to duplicate the line in order to get the power transmitted. It is only a few years ago that my firm were considering transmitting some power by an overhead line for a comparatively short distance, but we had to give it up because, at that time, the voltage that we thought it possible to work at was so low as to make it impossible to get enough wires on to the pole. If we could have used a higher voltage, such as is now possible, we could have done it very much more cheaply than we actually did do it by the use of cables.

Mr. Stubbs. Mr. A. J. Stubbs: One or two references having been made to Post Office practice, it may be in order for me to make a few remarks in that connection. With regard to aluminium wire our experience is only of wire as it was made ten years ago, when, during a gale which did not affect any copper wires in the district, the whole of some aluminium wire put up for trial utterly collapsed, actually breaking in nineteen of the spans. This failure led us to make some factory experiments to see whether we could get over the difficulty. Our tests showed the great importance of differentiating between the elasticity of the wire when subjected to strain for a short period and its elasticity when subjected to constant strain. This is noticeable, of course, with copper as well as with aluminium wire, but to a much less extent. For instance, a 40-ft. length of 150 lbs. copper wire, with a breaking weight of 490 lbs., when loaded for a short time to 110 lbs., showed very slight elongation, and recovered absolutely as soon as the load was taken off. When loaded for 24 hours it extended $\frac{1}{64}$ in.; when loaded for three days it extended $\frac{1}{32}$ in.; and its maximum elongation of $\frac{3}{64}$ in. was attained after being loaded for 14 days. In the case of the aluminium wire the stretching was far greater, and the permanent elongation under the same conditions continued to increase for over six weeks. Referring to another series of tests with 36 ft. samples of aluminium; some loaded for 150 days with 200 lbs. elongated as much as $3\frac{1}{2}$ in.; and others loaded for over 100 days with 150 lbs. showed a 1-in. stretch, and had not reached the limit. As a result of several thousands of these readings we came to the conclusion that, in considering the quality of elasticity from the practical standpoint, it was desirable to take the highest load at which no permanent elongation took place. Comparing in that sense pure aluminium, aluminium bronze, and copper, we found the result for aluminium was only 2,900 lbs., for aluminium bronze 3,200 lbs., while for copper it was 8,000 lbs. per square inch.

Our main difficulty in regard to use of aluminium was, no doubt, the matter of soldering, as, so far as telegraphic and telephonic circuits are concerned, our experience even with copper wire has uniformly been that the McIntyre or other form of mechanical joint is not satisfactory. The Britannia joint that we use is stronger than the wire itself, and, of course, gives us a perfect electrical joint.

The only other point I should like to refer to is with reference to the insulator which has been placed on the table by Mr. Rayner.

For considerably over thirty years the Post Office specification for insulators has secured that the insulation does not depend in the least upon the glazing. It is possible to take a British-made Post Office insulator, entirely remove the glaze, and not reduce the insulation at all. The glazing is merely to reduce the tendency for dust to adhere. Mr. Stubbs.

Mr. F. V. T. LEE: The subject of these papers has been of peculiar interest to me since I have until quite recently been associated with long-distance power transmission engineering in California, and it is interesting to note the great differences of opinion there are, even among those similarly situated. In other words, I cannot subscribe entirely to all the authors have said. The papers are very broad, and consequently it is hardly expected that all points would be covered. However, taking the points as they appear, I would like to call particular attention to the absolute necessity, in power plants of this character, of having what I think Mr. Taylor calls condensers or synchronous motors distributed as much as possible along the system. It is possible to operate without synchronous motors, *i.e.*, with rotary converters, but synchronous motors give much better control of the regulation and power factor of the system; added to which they have in our experience in California been found to be very much more satisfactory, particularly where it is necessary to transform from alternating current to direct current for railway purposes, since the motor generator maintains the direct-current voltage constant, which is of course desirable. In the system of which I speak, there are eleven water-power plants with an aggregate capacity of 67,000 k.w. operating at 60 kilovolts, the whole being more or less tied into one network, and on that system it was absolutely impossible to regulate the delivered voltages from the plants. The best mean voltage for the system at the various times was maintained at the plants by orders from the power despatcher. At all sub-stations the transformers are equipped with variable taps on the low-tension side, which are brought out to a rotary switch or "regulator head" (operative under load) to give a 20 per cent. range of voltage, 10 per cent. above and 10 per cent. below normal, the lighting circuits themselves being provided with automatic regulators. Some such provision is absolutely essential for a lighting service on large systems, where large blocks of power come on and off the lines without notice. Regarding future limitations of voltage, I am inclined to think that the local authorities, or official bodies appointed to control the rights sought by power companies, will have more to say and will have more effect on the upper limit of voltage than will the corona. Local restrictions are already felt in the West, but we are now coming to the point where a Public Service Commission, made up of experienced and qualified men, will deal with the matters arising between the public service corporation and the public—individual, corporate, and municipal—instead of the local boards made up of farmers or other locally elected representatives, necessarily without qualification in technical matters. The States of New York and Wisconsin already have boards of Mr. Lee.

Mr. Lee. this character, having the further power to fix rates and prevent wasteful competition. In California, power companies holding charters from the State are vested with the right of "eminent domain," giving them a right of way over the public roads, subject to the rights of prior occupants—telephone, telegraph, etc. They can also "condemn" or expropriate a right of way over private property, subject to judicial or arbitrational values of the damage—a right only exercised as a last resort on account of delay and legal difficulties, but these rights do not interfere with the police powers of the local municipalities. In several cases of my experience where lines passed within the boundaries of the municipalities, but without the settled portions, it was actually necessary to take down the lines and build round the town, to avoid the restrictions that the local authorities desired to impose. However, with a Public Service Commission, or a Power Commission, in existence this and similar troubles will be avoided, but I am inclined to think that 100,000 volts or thereabouts will remain the limit for some little time.

I have had some very sad experiences with lightning arresters of the gap type. Ten years ago, when these were in vogue, it was necessary to put up a building very nearly as large as the power station to house the arresters. When a discharge took place, it often shut down the plant, and after the arresters were cut out all hands cleared away the wreckage. New varieties of resistances and new types and arrangements of gaps were tried, with the same disastrous results. Eventually the old horn-type arrester was substituted and is now used entirely on the Pacific Gas and Electric System. So far, we have not been able to get any satisfactory resistance to operate with them. However, I think the horn arrester with a resistance is the most satisfactory solution in sight. Some of the other power companies in California have the electrolytic type, but I have not been fully advised as to the results obtained. I agree with the suggestion that split conductors are necessary for service, but it is necessary to go further and split the pole lines; that is to say, a single pole line carrying two circuits is very little better than a single pole line with one circuit, because it is very difficult to repair a line with a live line on the same pole, although it is done. Further than that, in most cases when one line is in trouble the other will also be affected. For continuity of service it is absolutely necessary to have two-pole lines, and these preferably, if it is not too expensive, should take different routes.

In small units I think 3-phase transformers are probably desirable where the saving in cost is material and the saving in floor space is necessary; but in large units, 1,000 k.w. or larger, it is better to instal single-phase transformers. I know of one case where a short circuit or some similar trouble within a 10,000-k.w. 3-phase transformer resulted in an explosion that not only blew out the case but did considerable damage to the power house, and the shock was sufficient to knock all the operators down. Similar short circuits in transformers, in my own experience, up to 2,000-k.w. capacity have not been accompanied by

any such evolution of force. I think, therefore, that this factor of the possible effect of a short circuit within the transformer must be looked to very carefully when large units are installed. While on this subject, I should like to add a plea that the insulation in high-voltage transformers should be as far as possible fire-proof. I have always specified that the insulation, particularly between the coils, should be of micanite or something of that sort. With a micanite-insulated transformer burn-outs are usually localised. As the extent of damage usually governs the time apparatus is out of service, this is a very important factor to the operator. The new switch suggested in the paper is very interesting. I regret that we have not had an opportunity of obtaining a description of it. After some fourteen or fifteen years' experience I have come to the conclusion that for 60,000 volts there is nothing better than a horizontal break switch with plenty of oil. We have had a great deal of experience with switches of all types and conditions, and ultimately developed one for our own use. This switch was illustrated, I think, in Dr. Marchant's paper last year.* It is a switch that has operated with perfect satisfaction up to the limit of the system on which it is installed. It is quite possible that in its present form it would not be satisfactory for 100,000 volts, but I think it likely that some time will elapse before switches that are entirely satisfactory even for that voltage will be obtained. Prolonged and severe service is necessary before a switch can be said to be satisfactory. Factory and short-time tests are not conclusive. Mr. Lee.

Another point that is mentioned in the paper is the new method of putting the series transformer on the insulators, or "bushings," of the transformers themselves. This unquestionably will minimise and tend to reduce the cost of the series transformers, which are very expensive. On the other hand, I hope that the manufacturers will develop a substitute for series transformers. I know of few things more deadly than 60-kilovolt series transformers in a station. It seems that a small transformer is demanded as an appendage to a meter—itself usually small. These transformers, when they are connected directly to the line, are a very great source of danger, and many serious accidents have resulted from their failure. With regard to the question of transformer connections, and the advisability of using either delta or star connections, I think in all the cases cited—and I know most of them—the simple fact is that the plants now operating on the star voltage started with the delta, and those that are operating on the delta hope to change to star. The transformers should always be insulated for the star voltage, even if they are bought to operate on delta. I should deprecate any system of false alarms for sharpening the wits of the line men or patrol men. I think the policy of false alarms of any character is bad. A very important question we had to consider on our system was the question of the operation of our telephone lines. The original telephone lines were strung on the main pole lines. Reliance on these, however, has been abandoned, more or less owing

* *Journal of the Institution of Electrical Engineers*, vol. 44, p. 423, 1910.

Mr. Lee. to the fact that when the pole lines were in trouble the telephone lines were in even greater trouble, and the result has been that most of the systems now lease lines from a telephone company on the telephone company's own pole lines; these lines are as much as possible away from the power lines. The lines on the transmission poles are then used for ordinary repair work, and for local work between stations as much as possible. Despatching and important business is transmitted over the leased lines.

The allowances for depreciation mentioned in Mr. Taylor's paper do not seem to have been questioned. Five per cent. depreciation on power-house equipment, 3 per cent. on buildings, and 5 per cent. on lines appears to me rather low. The very important factor of obsolescence may, in the case of electrical apparatus, exceed even that figure itself. With regard to the question of poles, I believe that wood poles will be necessary for certain classes of work for some time to come. Unfortunately, however, we are not so situated, even in California, that we can cut our poles down as we go along. The poles used in California are usually selected cedar poles from Oregon and Washington. The life of our poles is uncertain; I think ten years is about a fair average. There are some poles that have stood for forty years, but there are also a number of lines on which the poles have stood only five years without stubbing or resetting.

Mr. Mordey. Mr. MORDEY: Are the poles treated at all?

Mr Lee. Mr. LEE: No, they are not treated, but the Federal Government have been investigating a cheap method of treating the butts with creosote or carbolineum by a natural impregnation. The concrete pole offers a great many advantages, were it not for the fact that the lines are usually in more or less inaccessible and rough mountainous places, and consequently it would be almost impossible to transport them. They are nearly as difficult to transport as the materials. Concrete, however, will probably be used more in the towns on the coast, more or less for ornamental poles, for the reason that we have a number of cement works near by, and cement is cheap. Wood is becoming more expensive, and steel even more so. Of course for a high-tension line steel is really cheaper on the life that is suggested of, say, thirty years, or even a lower life. The only basis for that life is that similar structures have stood. That is to say, the predecessor of the present transmission tower is the American windmill tower; that tower has stood pretty well, and a great deal of experience has been obtained from it; in fact, the first steel tower line on the American continent was built in Mexico some eight or nine years ago, and was built of windmill towers with a pipe extension at the top. A good steel pole, however, is very much needed, but so far we have not been able to develop one with the requisite strength, a small base, and at the desired low cost. These are needed for lines that run along the highways and similar places, where the cost of maintenance of wood poles is high (although not any more so than in other places) and towers are out of the question. We have had no difficulty with long spans. The general construction

now is to use ten towers and twenty poles to the mile. Until recently forty poles to the mile was the usual construction, but owing to the cost of the insulators and insulation troubles it was found that a cheaper and better insulated line was obtained by taking out every other pole in the line; subsequent lines were built with twenty poles to the mile. The cost of the insulators is a very large factor on these lines. The flexible structures we have not tried and do not know very much about. The experience with insulators that was mentioned to-night is very interesting in that we had a similar case fourteen years ago on one of the first lines built. We then had porous insulators, but nowadays I do not think that the high-tension insulators depend at all upon their glaze for their insulating properties. The specification usually says that they shall not. The suspension insulator has rendered possible the 100,000-volt lines. There is still one point in that connection, however, which has to be developed, and that is a successful design of the strain suspension insulator. This is the insulator that is arranged horizontally and not vertically, and it is these insulators on the anchor tower that take all the strain. The first type developed was the interlinked insulator, in which the mechanical links actually interlinked with each other although there was porcelain in between. Those, of course, were absolutely safe, if the links held, for the reason that if an insulator was shattered there was still the metallic link connecting up the remaining ones. Considerable trouble was experienced with the links, and cemented connections were used, but these also have given some trouble—how much I am not prepared to say, as I have never used them. But I look on the present design of strain insulator as leaving much to be desired. Mr. Lee.

Road crossings are a very real question with us in the West, and I see it is the same here. We first erected elaborate cradles and nets to catch the wire, but found great difficulty in keeping them up properly. Now the general practice seems to be to build the line so strongly and so carefully, if need be, with messenger wires and other devices, that there is very little possibility of it coming down. I am rather in favour of a device which has been used in Colorado, known as the drop-out connector. The moment the strain is released on the wire by the wire breaking, the line disconnects itself by a ball-and-socket arrangement at each end of the span. I have had some field tests made with this apparatus, and find that it works splendidly, and that the conductivity is quite good. The American Institute of Electrical Engineers in conjunction with the railway companies are now in conference to determine upon standard designs for crossings. There is one point I would like to emphasise, and that is the absolute necessity of having a relay plant where cities or towns of importance are served from long-distance lines. I do not think it is possible, for anything like the expense that a relay can be put down for in a town, to duplicate the lines sufficiently to guarantee the service. That statement, I know, is somewhat heterodox; at the same time, from my experience in operating in two large cities, Oakland and San

Mr. Lee. Francisco, we have found it necessary to keep a spare plant on the line at all times. In the large cities, theatres and lifts and other very important services cannot be interrupted, and there is absolutely no other way of guaranteeing continuity of service. For street railway purposes good service can be given with gas-engine relays. Gas engines are built that can be put into service immediately that the call is given, the men, of course, being on duty and the gas being in the holder. We have put a 3,000-k.w. gas engine on the line in 35 seconds. In no case have we been longer than 4 minutes on an ordinary service, and the average is usually about 1 minute—that is, from the time a message is received by the operator and the signal given. The success of power transmission for the large cities depends entirely on a proper guarantee of service. The smaller towns, street railways, mines, and similar loads, can be taken care of by duplicate lines. After a certain point it is cheaper to put in additional standby plant than it is to put in additional duplication of lines.

Communicated: Many of the station wiring layouts illustrated in Mr. Taylor's paper are open to criticism on account of the complexity involved by the relays and other automatic devices. In my experience the simplest and almost elementary arrangement of switching is the most desirable. Even the most simple arrangement will introduce sufficient complication occasioned by the distant control of switches necessary in high-tension plants. Furthermore, in most cases, time-limit relays and other automatic circuit-breaking devices are a positive detriment to continuity of service, since, among other things, they tend to cause the operators to place too much reliance upon their action. Control by well-trained and experienced operators is much more reliable at the power plants. Rates are always a moot question, and if only the consumer would look upon the matter in the same analytical way and from the same standpoint as the power company, no trouble would ensue. All equitable rates are based upon a "standby" or "readiness to serve" charge plus a charge for the energy consumed. Many opinions exist among engineers as to the exact relation these should bear to one another. The consumers are mostly of one opinion; they do not like to be charged a variable rate, since it runs up their costs when their output is low. In many cases it has been found possible to give flat rates per kilowatt-hour, with a monthly minimum, and there are many loads that a power company can afford to handle in this way with justice to itself; for instance, cement mills, gold dredgers, electrochemical works, and large mines (where the variable and the hoisting loads do not form too large a factor). The point I am endeavouring to make is that it is very difficult for a power company in competition with cheap fuel to lay down too many hard-and-fast rules in the matter. Building up the load factor by "off-peak" loads will do much to simplify the rate question. Wooden pins have been entirely abandoned in the West, iron and steel being used exclusively. Further, where wooden cross-arms are used, the pins are connected together electrically and in most cases connected to

earth by a wire running down the pole to a ground plate. I cannot feel that the overhead ground cable carried over the steel tower lines has, as yet, established its value and necessity as a line discharger—or otherwise. I do believe, however, that it is a very valuable adjunct to the line from the standpoint of stability. I agree with Mr. Taylor that wooden flumes should be avoided wherever possible, and also that they are an endless source of trouble and worry. On the other hand, it must not be forgotten that the alternative is often a long and expensive rock tunnel, the cost of which, at the outset, might be prohibitive to the undertaking. I have been much interested by the contributions to the discussion on the subject of aluminium wire, and believe that we in California were the first to use it for power purposes some ten or twelve years ago. At the present time the Pacific Gas and Electric Company have about 13,000 tons of this wire in use, including some spans in excess of 1,200 ft. Some of the earlier installations consisted of solid wire, but owing to the lack of experience in making the wire at the time, a somewhat uneven product resulted. The solid wire was replaced with stranded wire, as it was felt that a more uniform product could be obtained. Solid wire is not now used. The wire used upon this system varies from No. 4 B. and S. (41,740 circ. mils) to 471,000 circ. mils, but is chiefly of No. 0000 B. and S. gauge (211,000 circ. mils). Screwed mechanical joints were used on the larger wires, and a flattened tube joint on the smaller ones. This tube joint differed somewhat from the McIntyre, which has two tubes; it is, I believe, fully as effective, and is applied in the same manner. For some years these joints have been abandoned on all new work and repairs in favour of a splice joint, which was found to have many advantages in the field, and was often necessary for emergency work if splicing tongs and tube were not at hand. The joint I refer to is made by unstranding the cable and interlacing the ends, as for an ordinary rope splice. A strand is then taken and wrapped or served around the other strands and cable, followed by another and another until all the strands have been treated in the same way. The resulting joint is neat, strong, and of good conductivity. Furthermore, it does not call for any special tools, and any lineman can make a good job. May I call Messrs. Matthews and Wilkinson's attention to slight errors on page 582 of their paper. The line from the de Sabla plant of the Pacific Gas and Electric Company (formerly California Gas and Electric Corporation) is really about 170 miles to Oakland, but the distances of transmission are often in excess of 200 miles; and while the capacity of that station is given correctly, the capacity of the system, of which it forms an integral part, is 67,000 k.w. The voltage of the system is 60 kilovolts, the deSabla plant operating at a slightly higher voltage owing to it being more distant from the centre of distribution. Mr. Lee.

Mr. M. Rosenbaum (*communicated*): With regard to the use of wooden poles, trouble has been experienced in South Wales in a few instances, due to what may be termed the "inflammability" of the wood. The trouble has been due to the wires coming off the insu- Mr. Rosenbaum.

Mr. Rosenbaum.

lators and falling on the cross-arms, burning them right through while still maintaining the continuity of supply; these wooden cross-arms are now being replaced by channel iron. This trouble has also occurred at angle poles, in this case the pole being burned through. No trouble has been experienced as yet due to the deterioration of the poles, but in view of trouble due to weakening of the poles at the base, it is intended to strengthen them with reinforced concrete. With regard to the transmission line, does not the configuration of the wires, as given in Fig. 30 of Mr. Taylor's paper, result in unbalanced capacity and external magnetic field? Would the author tell us whether the wires are transposed along its length to neutralise these effects? As a result of using extra high voltages and the consequent ionisation of the air surrounding the wires, has there been any evidence of the formation of nitric acid on the conductors and consequent corrosion? Although the use of the ground wire certainly tends to safeguard the transmission system against atmospheric disturbances, yet I do not think its use is warranted in this country, since we do not experience such serious disturbances here as in America, while its use only adds to the cost to the system and is a source of danger due to the fact that it is liable to break and fall on the live conductors. Atmospheric disturbances are manifested in three different ways: First, direct stroke. I doubt whether the ground wire would be of any avail if this happens. Secondly, electrostatic induction. Here the ground wire when placed above the conductors acts as a shield to the system, and in order to be more effective the ground wire should be of high conductivity and large cross-section. Thirdly, electromagnetic induction. Here, again, the ground wire safeguards the system, since the ground wire together with the earth acts as a short-circuited secondary, and thus the energy is dissipated in these closed circuits. An additional loss takes place in the line due to the electromagnetic action of the system on these closed circuits formed by the ground wire and earth along its length. To find out an approximate value of this loss the case of a transmission line has been taken transmitting 40,000 k.w. at 110,000 volts, the frequency being 60. The configuration of conductors, as shown in Fig. 30 of Mr. Taylor's paper, has been taken, and the length of line assumed at 200 miles. This loss came out to about 40 k.w. with the full-load current flowing in the line. This loss varies as the square of the current and the square of the frequency. Thus for low frequencies it becomes inappreciable, but with a frequency of 60 and with low-voltage systems and large currents this loss may become quite appreciable.

The method of obtaining the regulation of the line as shown on page 541, although only approximate, yet gives sufficiently accurate results, and has the advantage of simplicity. The reactance factor (l_r) should be $\tan \phi_r$ and not $\tan \phi_r \times \cos \phi_r$. The expression, "equivalent resistance per mile," is a peculiar term to use, and has no physical meaning. It would have been interesting if Mr. Taylor had given further particulars with regard to Table II., such as size of plant, length of line, voltage of transmission, etc. I do not know the facilities for

obtaining coal at these centres of distribution, but it seems to me that if coal is plentiful a district taking a large load from these companies could generate their own supply and save on the transaction. This has been found to be the case with certain collieries in this country, and in many instances they generate their own supply rather than obtain it from the power company serving their district. The charges as given in Table VII. do not seem to me to be theoretically correct, as although there is a reduction per kilowatt-hour for the generating plant for an increased consumption, the difference between A and B remains at 0·5 of a penny. Thus there is no reduction so far as the transmission line is concerned. Mr Rosenbaum.

Mr. A. W. Isenthal (*communicated*): I am particularly interested in the remarks by Mr. Taylor on the question of lightning discharges, and am pleased to note that he, too, has come to the conclusion that the frequency of such discharges is to be reckoned in thousands or even millions of cycles per second. So many endeavours have been made to disprove this fact that it is quite refreshing to come across such an authoritative statement as this. Mr. Taylor says that if the inductance of a choking coil which is to check surges on transmission lines is of small value, a corresponding reflection might take place, allowing the surge to pass through the coil. But the object of the choke coil is really two-fold; and in any case its self-induction for high-frequency current should be very high. I say advisedly "for high-frequency currents" because we cannot go beyond a certain value of inductance for ordinary alternating currents without having a considerable loss of energy. If it is placed in front of the lightning arrester, then it may serve to decrease the steepness of the incoming wave, but if placed behind the lightning arrester—which is the usual practice—it should reflect the whole surge back to the line, and, at any rate, prevent the surge from entering into the apparatus. The simplest way to obtain a choke coil which has a high inductance for high-frequency currents and a medium inductance for the ordinary line current is to utilise the well-known effect with high-frequency currents, obtained by using for the material of the choke coils a good quality of iron. Mr. Taylor limits his choice of lightning arresters for the transmission lines to the aluminium type, the multi-gap type, and the water-jet, which he discusses; and I am naturally sorry to see that the condenser has not been included in this array, for the reason that in an earlier part of the paper we are told that the lightning arrester is advantageous, when set correctly, for the protection of the apparatus from surges. Mr. Isenthal.

I quite agree with Mr. Taylor, and the point cannot be insisted on too strongly, that, as he puts it, "The effect on the line caused by a flash-over of the lightning arresters may cause a heavy disturbance on the whole system, since the reaction set up tends to increase the current on the line in proportion to the square of its original value." But this is due to the fact that the various lightning arresters which he mentions all possess a spark-gap, and such spark-gaps in conjunction

Mr. Isenthal.

with the self-induction, the capacity to earth and the apparatus to be protected, constitutes an oscillation circuit in which high-frequency currents are set up; and the surge tension produced by the breaking of the arc is, of course, proportional to the square of the current. This is the reason why all such gaps require resistances in series with the earth wire, and constitutes also a severe limitation of their efficiency. We have, in fact, to choose between two evils, either we prevent such oscillations by damping them out with an ohmic resistance, in which case, as just stated, the discharge capacity of the arrester will be limited; or we have to forgo its safeguarding resistance, in which case high-frequency phenomena may supervene and we may develop a dead earth of the line if the line current flows across the ionised spark-gap. The necessity which Mr. Taylor emphasises, of setting the lightning arresters correctly, is naturally obviated when using condensers as lightning arresters, because there is no spark-gap with these. There is no damping resistance either, as the line current of low frequency cannot pass through the condensers (the capacity of which is always small), whilst the high-frequency disturbance, on account of its extremely high frequency, passes through the condenser to earth at an enormous rate, provided the self-induction in the condenser circuit be negligible. Finally, I should like to say that, in my opinion, power engineers do not differentiate sufficiently between the various forms of lightning troubles, and consequently some confusion and disappointment arise in connection with the selection of a suitable type of arrester. The water-jet can only justify its adoption when it is realised that there might be static charges on the line. It is quite useless for the purpose of dealing with high-frequency phenomena or with pressure surges. On the other hand, the horn arrester is quite useless for the purpose of discharging static charges on the line, because it will only act when the static voltage has risen to several thousand volts. Again, no condenser would protect the generator or transformer or cable from surges due to internal causes, such as the breaking of a short-circuit, etc.

Mr. Wade.

Mr. CHRISTOPHER WADE (*communicated*): Mr. Taylor's paper appears to deal principally with American systems where higher voltages, longer spans, etc., prevail, on account of more open country. For voltages so far used, and conditions in this country, where there are not very long clear runs, wooden poles have been, and are, successfully used. Their strength has been amply demonstrated by tests we made a few years ago, also by Post Office tests, etc., and their durability, when properly creosoted, is shown by the number in use for all purposes in this and other countries. I see Messrs. Matthews and Wilkinson say the average life of steel towers is 30 years. I do not doubt it, but then this is only attained by continual painting. They also say the average life of wooden poles is only 12 years. I presume this refers to unpreserved poles (greatly used, I believe, in America). I consider the average life of properly treated wooden poles to be at least 25 to 30 years, and no doubt the English Post Office and

the National Telephone Company will bear me out in this. As to cost, I believe wooden poles are considerably cheaper than steel ones of equal size or strength, and of course the cost of overhead lines run on wooden poles is only a fraction of that of a similar underground line. A great many people raise objection to the use of creosoted wooden poles on account of the oil oozing out of same and their being dirty to handle. I might say that there is a new process of creosoting which is called the "Ruping" process and is a German invention, in which I am interested, and by this all surplus oil is extracted before the completion of the process and the poles left perfectly dry; and this has already been tested for a number of years and is more efficient and satisfactory than the ordinary method. Mr. Wade.

Mr. E. KILBURN SCOTT (*communicated*): I was interested to hear Mr. Trotter speak well of wooden poles, because it was my business to interview that gentleman officially about the transmission lines of the North Wales Power Company in 1902, and at that time I rather gathered that Mr. Trotter was favourable to high steel towers. In those days, even to talk about extra high tension lines overhead was like holding a red rag to a bull, and my position was the more delicate because some of our wooden poles had already been contracted for. I decided on the H poles, because they look better than A poles, and, if necessary, nine wires can be carried on three cross-arms. Any one visiting Snowdon to-day can see what a good job such creosoted H poles make. Some have now been up about seven years, and although in very exposed situations, not a single pole shows signs of giving way. They are a little marked with the linesmen's climbing irons and somewhat piebald on the south-western side, due to the preservative being washed out. The H pole is about four times as strong as a single pole and is cheaper. Having a wide transverse base, it can be depended on to remain upright however much the transmission line is buffeted by hurricanes. Nothing looks so bad as poles leaning different ways; the eye instinctively lines them up, and any deviation is as jarring as seeing a striped wall-paper out of plumb. The new Ruping process of creosoting poles which has been adopted by Mr. Wade, of Hull, should cheapen the cost of poles, because 4 lbs. per cubic foot penetrates and preserves as well as the 12 or 14 lbs. previously used. The timber is first placed under compressed air, and then creosote is injected at a higher pressure. When the pressure is taken off the compressed air drives out the surplus oil. Transmission problems in other parts of the world have an interest beyond the technical side in that climatic and zoological conditions have to be studied. For example, the air of coast towns of semi-tropical countries generally has great humidity at certain times of the year, and in some cases it may carry a good deal of salt. On the coast of Australia, for example, the humidity is sufficient seriously to affect the insulation of electrical apparatus, and in Sydney, salty deposits have regularly to be washed off the roofs of the tramcars to keep up the insulation of the trolley pole. The inland parts of these same countries generally have a remarkably dry atmosphere, giving high insulation. Mr. Scott.

Mr Scott. So much is this the case in Australia that it is quite a common thing to use the top fence wire for telephone circuits. At gates there is a connection which can be raised up for horsemen to pass under. The worst trouble in some parts of the interior is the dust. A Broken Hill dust storm would, I think, try a transmission line quite as much as a Canadian blizzard. Speaking of snow reminds me that I ought to correct the popular impression that there are no snowstorms in Australia. I have seen snow lying over a foot deep in the Blue Mountains, only 70 miles west of Sydney, where a high-tension transmission is now going through to light towns on the Blue Mountain road. Also at the old mining town of Kiandra, about 200 miles south of Sydney, I have travelled about for a week, on Norwegian ski, and the snowdrifts in some places were 10 ft. deep. The proposed site of the new Federal capital is not far from there, and there may be a transmission line in the district some day. To show the peculiar conditions that one may meet with, I remember visiting Rotorua, in the North Island of New Zealand, some years ago; it is a Government tourist resort, and well lighted from a hydro-electric plant a few miles away. All the wires are overhead on steel poles, for the very good reason that in some places the earth a few feet down is unpleasantly hot. When digging a post hole the man has to keep jumping out to cool his feet. Zoological troubles mostly take the form of white ants and monkeys. Given time, white ants will eat their way up the inside of a pole, along the cross-arm and up the wooden insulator pin; in fact, some of the feats of these busy little borers read like fish stories. The only way for the untravelled, is to believe all or none, because the absolutely true stories sound quite as improbable as those which are invented. Creosote will not stop a white ant, and the only really effectual way is to use a metal pole or, at any rate, a composite pole iron at the bottom and a wood pole above. The inside of the iron base must have a layer of concrete, or they will build up an earth tunnel inside until they reach the wood. An ordinary spiked corona will stop a bare-skinned native but not a monkey, because he learns to make a back round it for the others to pass over. The only way to deter them from electrocuting themselves is to wind a barbed wire round the pole, securing each turn so that it does not slip down.

Some time ago I had occasion to summarise particulars of an accident in California, when several miles of 60,000-volt line were thrown over by a hurricane. Huge steel towers were blown right over. The accident was partly due to poor foundations, but it could not have happened if there had been considerably less surface for wind pressure. The point is, how to reduce that surface. I believe that the steel tower method of carrying high-tension lines is faulty. The tower is an outcome of the pole, and both were necessary when each wire was carried by a pin insulator underneath. Now, however, the usual plan is to suspend each wire from a number of link insulators, so the necessity for an under support has gone. A much better job would be attained by having two poles and span wire as shown in Fig. A. A shows the insulators suspended from the span wire in much the same

way as they are now suspended from steel towers. B shows some of the insulators forming part of the span wire, and this has the advantage of reducing the sideway swing. It will also be noted that the wires are raised higher from the ground and that they are disposed in triangular fashion. C shows a design for an iron base with the material arranged to most efficiently resist the stresses due to the span wire. A method is also suggested for easily raising the wooden pole into place. Such an Mr. Scott.

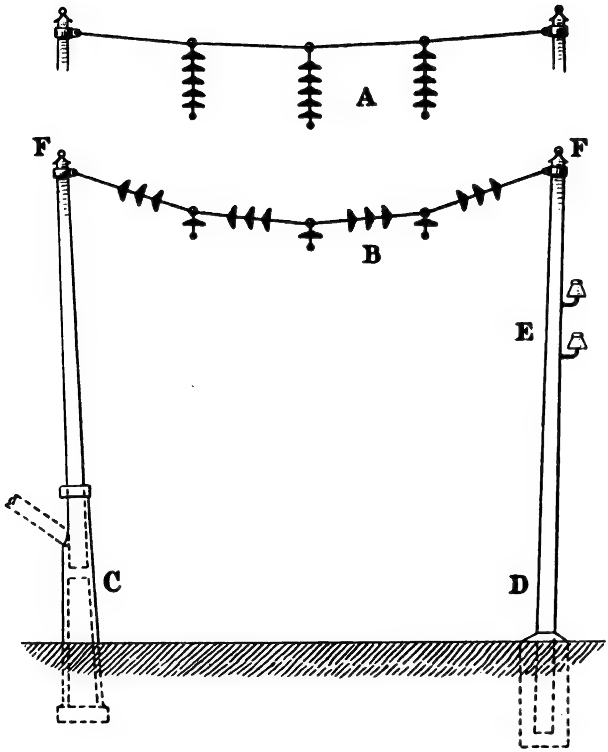


Fig. A.

iron socket would be necessary where white ants are feared, but in most cases the wooden pole would be set directly in concrete as shown at D. The telephone wires would, of course, be carried on the outside of the pole as at E, and the earth wires at F. The craze for steel lattice towers has, I think, gone far enough. According to the drawings given in the paper, a tower 50 ft. high to the lowest insulator covers a space about 17 ft. square, and the transmission wires are, say, 6 ft. apart. Now, if a span-wire construction such as I suggest is employed with steel poles, they would have to be $6 \times 4 = 24$ ft. apart. That is to say, only 7 ft.

Mr. Scott. more than the steel tower one way. The under gear of the span-wire construction would therefore cover much less ground. But, as a matter of fact, wooden poles alone or wooden poles in iron sockets could be used, in which case the poles might be, say, only $(4 \times 2) + (6 \times 2) = 20$ ft. apart. The great objection to wooden poles is that they may rot at the butt or be attacked by insects. These troubles are entirely prevented by having iron sockets, and at the same time a shorter and therefore much cheaper pole will do; or, for a given length of pole, the transmission wires are higher. The right of way for a transmission line such as I suggest would not cost any more than for steel lattice towers; indeed, farmers are more likely to look with favour on occasional poles about 9 in. diameter than on steel towers covering 17 ft. square. The iron sockets would make convenient and effective rubbing posts for his cattle if nothing else. Writing of farmers suggests the query as to whether these high-tension lines have any effect on the vegetation underneath and to leeward. The direct-current transmissions on the Thury system ought to have considerable effect (probably of a droughty nature) if Professor O. Lodge's and Mr. Newman's experiments at Bitton are any criterion. In conclusion, I would like to protest against the pessimistic insular tone of some of the speeches. Because this country is small and the coal beds widely distributed, some engineers bewail the lack of the opportunity to run transmission lines for hundreds of miles at 60,000 or 100,000 volts. They seem to overlook the wide spaces of the Empire, and if they speak of India, Australasia, South Africa (or even Canada) at all, it is as if those places were foreign countries. Surely a more sensible attitude would be to speak of them as one speaks of Yorkshire, Fifeshire, or Donegal. The business opportunities of all parts of the Empire should be as carefully nursed as if they were hundreds instead of thousands of miles away. Canada is a little too near the United States for electrical engineers in this country to expect much business, but in South Africa, India, Burmah, Straits Settlements, and Australasia there is much to be done if it is followed up. Even drought-stricken Australia has some quite respectable hydro-electric plants at Launceston and Hill Grove. The Waipori Falls transmission that supplies the lighting and tramways of the City of Dunedin through a 30,000-volt transmission is a fine installation, and New Zealand is about to put in hand some big developments.

Mr. Gall. Mr. JOHN R. GALL (*communicated*): With reference to some remarks in the course of the discussion, that jointing sleeves were not satisfactory for telegraphic and telephonic purposes, I should like to point out that the National Telephone Company made a careful investigation some six years ago as to the suitability of this type of joint for telephone work. With regard to the mechanical efficiency the tests showed the comparative strengths of the jointed wires and similar unjointed wires as shown in table opposite.

Although, as will be seen from the accompanying table, the strength of a copper wire jointed with sleeves is less than the same wire with soldered joints, it is found in practice to be satisfactory, as it is

considerably above the yield-point, which does not exceed 65 per cent. of the breaking load of the wire. As to the electrical efficiency, a span of 40 yards of 40-lb. bronze wire, containing 50 copper sleeve joints in series, was erected on the roof of Telephone House, Victoria Embankment, London, in January, 1906; the conductivity of this span was found to be quite equal to that of a similar length of unjointed wire, and remains so at the present time, and no variation in the continuity has ever been detected. In addition, a practical trial on a large scale was made in several districts under Mr. Gall.

Description of Wire.	Strength of Wire Unjointed.	Strength of Wire with Soldered Joint.	Strength of Wire with Copper Sleeve Joint.
40-lb. bronze	100	90	92
100-lb. copper	100	97	83
150-lb. copper	100	93	80

varying climatic conditions, and extending over several years. These trials proved the sleeve joints to be efficient, both mechanically and electrically. As a result of this investigation the sleeve method of jointing wire was adopted generally by the National Telephone Company, and there are at the present time several millions of these joints working entirely satisfactorily in its system. I might add that copper jointing sleeves are used almost exclusively by the principal telephone undertakings in the United States, the Continent, and the British Colonies.

Mr. R. G. Isaacs (*communicated*): On page 512 the author states that a further increase in voltage is limited by the corona effect. When this increase becomes necessary, could not the limit be raised by the adoption of a stranded conductor with a hemp core? The objection to this would of course be the increased wind and snow load, but I should think that this would be more than counter-balanced by the saving of copper due to the higher voltage, the considerable reduction in the "skin effect" and in the inductance. As regards the wiring lay-out for these extra high-tension systems, is it not necessary to have a choke coil and arrester between the automatic switch and the transformer? Otherwise the former will be unprotected against a surge due to the opening of the switch. Mr. Isaacs.

Discussion before the Newcastle Local Section, January 30, 1911.

Mr. C. Vernier: Both the papers before us for discussion deal with a class of work of which we have no examples in this country. I refer Mr. Vernier.

Mr. Vernier.

to the transmission of electrical energy in bulk from one district to another which may be situated from 100 to 250 miles away. The papers have, therefore, to be considered with these conditions in mind, as the methods described, such as the use of suspension insulators and steel towers, have been found necessary chiefly on account of the extremely high voltages adopted, that is, from 60,000 to 100,000 volts, whereas the necessity for voltages exceeding 20,000 volts has not, so far, arisen in this country. One scheme on these lines for transmitting electrical power from the coalfields in the Midlands to the Metropolis has been projected, but has not come to a head, and it is doubtful if such schemes will be found necessary for many years to come, in view of the special conditions existing in this country. These conditions are essentially different to those existing in America, where great waterfalls are situated at remote distances from the centres of population, but no doubt even there, in the course of time, manufactures will tend to centre round the sources of power, a procedure already in progress at Niagara. Perhaps before we reach that happy state of things foreshadowed by our President, Mr. Ferranti, in his Presidential Address last year, when electricity will be obtainable for all purposes at about $\frac{1}{10}$th of a penny per unit, the great towns and centres of manufacture will be linked up by ring mains of enormous capacity, fed from gigantic power-stations situated on all the big coalfields, but this day is not yet. Turning now to Mr. Taylor's paper, on the first page of which he mentions some of the advantages of direct-current transmission, I believe the only examples of such work are to be found in Switzerland and France. The system has been developed by M. Thury, who has in an admirable manner surmounted the many difficulties inseparable from the construction of direct-current machinery for generating up to voltages of 57,000 volts. As there may be some present who are not familiar with that system of transmission I might briefly outline its chief features. The line current is fixed and remains constant at all times, all variations of load being dealt with by raising or lowering the generator voltage. All the generators and motors are series-wound machines. To start up a generator the dynamo is run up independently on short circuit until its current equals that of the line, after which it is cut into the line. The variations of load are dealt with by an automatic regulator, which raises or lowers the speed of the generators and so increases or reduces the line pressure. Motors are started up by being switched on to the line with their brushes in a position at right angles to the normal working position, and these brushes are immediately brought forward by an automatic gear until the motor attains its proper speed. The line may be earthed on either pole or at the middle point, so that the line voltage is distributed partly above and partly below earth. A breakdown of a motor is not serious, as, if one becomes short-circuited without an earth, the line current simply passes through it, the generators lowering their voltage automatically until eventually the short-circuited motor absorbs only sufficient volts to overcome its ohmic resistance. If broken down to earth, the main

Mr. Vernier.

line earth can be immediately changed over to the same pole as the broken-down motor is on, if the earth is not already on that side, or the line freed from earth by the blowing of a fuse in the earth circuit. The motors can have their mechanical power applied direct to machinery or can be utilised for driving generators, which may be either direct-current or alternating. The advantages on the line itself are that only two conductors are required as against three for a 3-phase system, and in some cases it is even suggested that only one is required if an earth return be used. The number of insulators is consequently reduced by either 30 or 60 per cent., and they need only be constructed to withstand the working voltage used on the line, and not $\sqrt{2}$ times as for alternating current. The power factor is fixed absolutely at unity, and not, as is usual, varying down to anything between 80 and 85 per cent. as in alternating-current transmission. Another advantage is that there is no charging current on the line and there can be no resonance under working conditions. In this connection it is interesting to note page 540 of Mr. Taylor's paper, on which he mentions a 100,000-volt line estimated to have an ultimate charging current of 20,000 k.v.a. The importance of the last three points must be emphasised as being strongly in favour of direct-current long-distance transmission. The most recent example I know of is the Moutiers-Lyons transmission in France, by which 4,320 k.w. are transmitted a distance of 112 miles with a line voltage varying up to 57,600 volts, the line current being fixed at 75 amperes. This scheme has now been in operation for the past five years. Turning to the question of steel towers *versus* wooden poles discussed on page 527 of Mr. Taylor's paper and page 567 of Messrs Matthews and Wilkinson's paper, all the authors seem to be unanimous regarding the advantages of steel towers, and for lines with voltages over 40,000 volts I do not think any one would be inclined to disagree with them. Both the papers give the average life of wooden poles as 12 years (see page 530 of Mr. Taylor's paper and page 567 of Messrs. Matthews and Wilkinson's), and as far as this country is concerned I cannot agree with them, for the life of Norwegian pine creosoted poles in this country in a large number of cases exceeded 20 years, so that a fair average would be more like 17 to 18 years.*

The figures given in the paper are probably based on American practice, where the timber used is chiefly cedar, chestnut, northern pine, and cypress, and where poles are generally used without any preservative treatment whatever, except for a coat of paint before and after erection. I am giving below some figures showing my ideas on the comparative cost of steel towers and wood poles for lines of 20,000 volts working pressure under local conditions, and as these figures were based on several assumptions I am inviting criticism with a view to arriving possibly at some more accurate comparison.

* *Electrical Review*, vol. 59, p. 343, 1906—statistics over 52 years and 3,000 000 poles.

Mr. Vernier.

STEEL TOWERS *versus* WOOD POLES.

Line voltage, 20,000 volts.

Line spans { Towers, 720 ft. / Wood poles, 240 ft.

Assumed life of towers, 36 years (see page 529 of Mr. Taylor's paper).

Assumed life of original galvanising, 9 years.

Assumed life of wood poles, 18 years.

Cost with Steel Towers—

	£
Tower	12
Erection	5
Painting after 9 years once every 3 years = 9 times at £1...	9
Wayleave charges, 36 years at £1 per annum	36
	62

Cost with Wood Poles—

	£	s.	d.
3–40 A poles complete, including erection ...	18	0	0
Painting	—		
Renewal of 3 poles once at £4 10s. each, including labour ...	13	10	0
Wayleave charges, 3 poles at 6s. per annum each = 18s. per annum for 36 years ...	32	8	0
	63	18	0

Turning to the consideration of line insulators, Messrs. Matthews and Wilkinson, on page 570, and Mr. Taylor, on page 534 of his paper, pointed out the great advance in the use of higher voltages which had

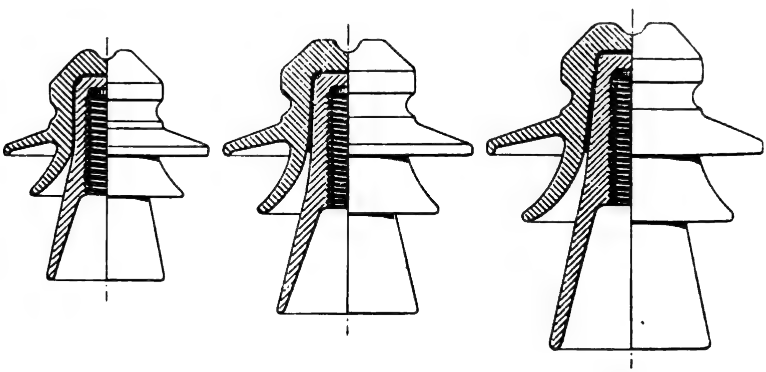


FIG. A. FIG. B. FIG. C.

been rendered possible by the use of suspension-type insulators. For voltages above about 40,000 volts one is compelled to use these suspension insulators. They are convenient as they can be adapted for all voltages by simply increasing the number of discs in series, and as any one disc withstands a very high voltage, the factor of safety on the

Mr. Vernier.

lower voltage lines can be considerably increased without much extra expense. I do not think, however, that there is any need to use them for anything below 30,000 volts in this country. I agree with Mr. Taylor that climatic conditions are a considerable factor in the design and satisfactory operation of an insulator. I might instance that the insulators originally used for 6,000 volts in my district (Fig. B), and for 20,000 volts (Fig. C), had recently been increased owing to the small factor of safety against arcing-over in wet windy weather, a danger which had been recently discovered as the result of tests on an actual line. These insulators had therefore been increased in size to Fig. C for 6,000 volts, and Fig. D for 20,000 volts. I might further point out that the insulators Fig. C and Fig. D are rated in Germany for 33,000 volts and 39,000 volts working pressure respectively. It has been found necessary also to give up entirely the use of the shackle type of insulator, which only has about half the factor of safety of a similar size of straight-line insulator. Straight-line insulators are now always used for terminating with a special heavy pin, as illustrated in Fig. D. The heaviest lines hitherto terminated in this way are 0·15 sq. in. sectional area, and the stress on the insulator about 1 ton. All the authors appear to recommend the use of an "earth" wire, but I am not very sure as to its efficiency. There is a great difference of opinion among transmission engineers as to the necessity for this earth wire, some believing in it, while others state that it is probably of some use, and others again that it is nothing but a nuisance. I have never seen the action of this "earth" wire discussed on this side of the Atlantic, and therefore put forward the following explanation.

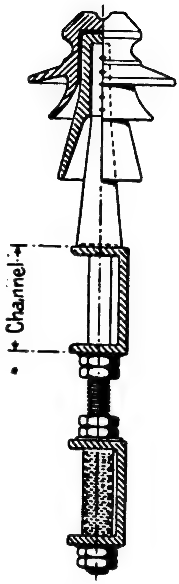


FIG. D.

Consider first a transmission line without an earth wire. If a cloud builds up with a positive charge above the line a negative charge will be induced on the line wires, the positive charge set free tending to pass to earth. If a delta-connected system is under consideration, this positive charge can only pass to earth over or through the insulation, whereas with a star-connected system earthed at the neutral point this charge can pass away to earth at this neutral point, provided the potential induced by the cloud does not build up too rapidly. If it should do so, then with either system there is a possibility of the insulation being punctured. When the cloud discharges instantaneously by a lightning flash there is an immediate readjustment of electrostatic potential to zero, which, as the discharge of the cloud is sudden, will be equally sudden and will probably spark over or through the insulation at the end turns of the windings of the transformers or other apparatus, due to the great self-induction they offer to a sudden discharge. Now

Mr. Vernier.

consider the case of an earth wire suspended above the live wire. This earth wire will also have a negative charge induced upon it by the cloud, the positive charge set free passing away rapidly to earth, but the negative charge on this earth wire will to some extent counterbalance the induced negative charge on lines from the cloud, so that the induced potential on the line wires is less than it otherwise could be. The ideal condition would be a screen of metal connected to earth surrounding the line wires, and the reason why two or three earth wires are more effective than one appears to be that this condition is more nearly approached than with one wire. The question is not nearly so simple, however, as here suggested, as this does not take into account the oscillatory character of the various discharges. It is important to have the "earth" wire thoroughly well earthed, as otherwise its usefulness in this matter is greatly impaired. An arrangement for earthing this wire used some years ago by the A.E.G. Company consisted in the use alternately along the line of earth stakes and spiders formed out of copper wire radiating about 10 ft. out from a central point to which the earth wire is connected, the various small wires and points and the large surface of these spiders tending to facilitate the static discharge of the earth wire, while the earth stakes take care of the heavier currents. I should like to call attention to the danger of working on overhead lines in certain conditions of weather if the line is dead and the switches are open at each end, thus disconnecting the line from the earth of the system. I have known several cases of shocks to workmen under such conditions. Coming to the question of resonance and surges, the former occasionally proves troublesome on very long lines, and this factor may be found to limit the distance of transmission by alternating current. There are some closely approximate rules in connection with this matter to which I might refer, as they are easily remembered and may be new to some members. Calling the capacity of the line K and the self-induction L, K multiplied by L is a constant irrespective of the diameter of the wires or of their spacing (*i.e.*, increasing the spacing increases L and decreases K in the same ratio).

The natural frequency f—*i.e.*, the frequency at which a single-phase line will resonate—is equal to the velocity of light over four times the length of the line in miles;* thus a line 400 miles long would have a natural frequency $f = 186{,}000/4 \times 400 = 116$ approximately, and a line of this length would tend to resonate to third harmonics with a frequency of 40. Fortunately, however, the voltage which would doubtless be employed on a 400-mile transmission would be so high that the corona discharge would probably relieve the line of any tendency to surge. I notice in the list of typical transmission systems given in Messrs. Mathews and Wilkinson's paper (page 17) that a good many systems are now operating at 25 frequency, and I think that probably it will be found that the adoption of this low frequency was on this account. Surges are liable to occur in switching out overhead lines if any form of circuit breaker is used which is liable to set up an arc, but with

* *Journal of the Institution of Electrical Engineers*, vol. 48, p. 521, 1908.

Mr. Vernier.

oil switches, which have the property of opening the circuit at or near zero potential, these are not likely to occur. With any form of air-break switch or an arcing short-circuit, however, surges are liable to prove serious. For the instantaneous stoppage of a short circuit the Merz-Price system of protection is useful, in that the switches are operated and the circuit is broken under oil before the arc ceases. Surge voltages are approximately independent of length of line, and an easily remembered rule, given by Professor Baum,* is that they cannot exceed 200 times the maximum value of C, where C equals the number of amperes broken. This maximum surge voltage $= 200 \times c x \sqrt{2}$. This has to be added to the ordinary maximum line voltage $\sqrt{2}\,\mathrm{E}$ (E being R.M.S. volts between line and neutral). For instantaneous interruption the total maximum voltage $= \sqrt{2}\,(\mathrm{E} + 200\ \mathrm{C})$, but is diminished by slowness of interruption or if the current is broken at some other part of the wave than the peak. It may be of interest to show how this works out in the case of two lines—one a 20,000-volt line and the other a 6,000-volt line—assuming the same current to be broken in each case, viz., 50 amperes. In the former case the maximum stress—

$$1{\cdot}4\,(20{,}000/\sqrt{3} + 200 \times 50)$$
$$1{\cdot}4\,(11{,}600 + 10{,}000) = 30{,}240 \text{ volts.}$$

In the case of the 6,000-volt line the figures are :—

$$1{\cdot}4\,(6{,}000/\sqrt{3} + 200 \times 50)$$
$$1{\cdot}4\,(3{,}500 + 10{,}000) = 18{,}900 \text{ volts.}$$

From this it is seen that the maximum voltage in the case of the surge on the 20,000-volt line can reach a value of nearly twice the maximum value of the working voltage to earth, whereas on the 6,000-volt line the maximum voltage under similar circumstances might reach a value nearly four times the working voltage. It is thus clear that the lower voltage lines are more liable to give trouble in that their factor of safety is less and the currents broken are usually heavier. Then again the surge frequency on long lines may not be very far from the frequency of supply, and this may cause resonance. The formulæ given in the paper on pages 513 and 540 will, I think, prove useful in ensuring that the section of copper used is large enough, but, like most problems of this sort, the section of copper is generally worked out from formulæ to three places of decimals, then the result is increased from 50 to 100 per cent. for future developments, the nearest standard size of wire to the result thus obtained being finally adopted. I agree with Messrs. Mathews and Wilkinson—page 574, paragraph (*g*)—regarding the standardising of a minimum size of wire on account of trouble experienced due to the formation of ice. The companies with which I am connected have standardised 0·05 sq. in. copper as the minimum size for their lines on this account. I must say, however, that I entirely disagree with the

* *Transactions of the International Electrical Congress*, St. Louis, 1904, vol. 2, p. 243.

Mr. Vernier.

statement in the same paragraph, so often met with, that wires will swing synchronously in any wind. I admit that they may appear to do so, but would suggest that those who wished to be satisfied on the point should erect a line with long spans and too small a spacing and await results, especially if aluminium wire be used.

Mr Welbourn.

Mr. B. WELBOURN: Referring to Fig. 1 in Mr. Taylor's paper, the suspension type of insulator involves quite a departure from English practice, and I am interested to know whether the unsymmetrical arrangement of the conductors has any influence on the capacity or charging current of the line. Although longitudinal ground wires placed above the line seem to be considered essential by the authors, I notice that they have been omitted from the line illustrated in Fig. 3. There appears to be no unanimity in American practice on this point, and in many of the recently erected lines ground wires have been left out altogether. I cannot see the force of using grounded earth wires above the line wires as a protection against lightning, and it appears to me to be bad practice to erect iron wire, which in time is bound to corrode and consequently fall and probably short-circuit the working conductors. I have discussed this question with many engineers on the other side of the water, and it seems to be generally agreed that the best practice is to run a galvanised iron wire below the conductor and to use it simply for grounding all metal work on the poles. The flexible type of tower is not new. I know of a line which has been put up in the Midlands; the results have been negative in so far as no trouble whatever has occurred. In Fig. 4 the formula given is wrong, as the lowest figure 3 is superfluous. Turning to Fig. 8, there is a practical point in connection with tying-in wires in lines liable to flash; in these cases binding wires should be taken some considerable distance along the line and so confine any arcing to easily renewable parts. In Fig. 9, in the G.E.C. type of suspension, even if one of the porcelains breaks, the line will not fall, as the metal parts form a chain. With regard to Fig. 13, I presume that the tests were made with alternating current, and should be glad to know the relative corona losses at high voltages with alternating and direct current. The value of the curve would have been enhanced as a practical record had the frequency been given. Fig. 14 would unfortunately not meet with the approval of the railway companies in this country.

Mr. Drummond.

Mr. A. L. E. DRUMMOND: The life of creosoted poles should be 40 years at least, and sleepers have been known to be perfectly sound after being 60 years in the ground.

Mr. Robb.

Mr. J. M. ROBB: My experience is that good creosoted poles may last for 30 years, but the average life is 25 to 30 years. Unfortunately, in telephone and telegraph work the necessity for altering or replacing poles from one cause or another tends to reduce the average life still further. There is also a further point which might be found hereafter to have an influence on the question. I understand there is an increasing difficulty in obtaining supplies of Norwegian poles, and that the Russian variety is to some extent being used. During the great snow-

storm last winter several poles carrying 40 wires broke under the heavy stress, and the impression I gathered was not so favourable to the Russian poles as to the older and apparently tougher Norwegian. In two cases the former appeared to be softer. With regard to the question of light gauge wires, I might say that this district was one of the first in this country to use copper wire for telegraph and telephone purposes, the wire then used being largely No. 14 gauge, weighing 100 lbs. per mile. This gauge, however, did not stand well against snowstorms, and for that and other reasons advantage was taken of the repairs to substitute a heavier wire in its place on the main lines. Mr. Robb.

Mr. J. PIGG: I am also of opinion that poles should at least last over 30 years. Mr. Pigg.

Mr. S. G. REDMAN: I should like to refer to the figure which has been suggested as giving the comparative costs of steel and wooden pole line construction. The papers dealt almost exclusively with the steel poles, and probably for the lines referred to these were the right thing. Nevertheless I am a firm believer in the use of wooden poles for transmission work in this country generally, and agree with the speakers who have criticised the assumption that steel poles have a life of 35 years. I might instance, as a case of the life of steel work, the steel chimneys of the Dublin United Tramway Company, which were erected about 1898, and through the walls of which, due to corrosion, it was possible to push an ordinary penknife at the end of ten years. These stacks have since been reinforced by ferro-concrete, and when put to work again, the expansion of the concrete has caused sections of the steel chimney to part company, so that the ferro-concrete construction is now being largely relied upon for the strength of the chimneys. With regard to the price of steel poles, £12 might be a fair figure for flexible poles suitable for straight-line work, but in this country, owing to wayleave difficulties, a large proportion of the poles are at corners, for which the flexible type of pole is not suitable. The number of steel corner poles would increase the cost of the work considerably. Wooden poles would, in my opinion, last 50 per cent. longer than Mr. Vernier has suggested, and I think that the case for them in this country is a strong one. With regard to the limitation of wooden poles, experience in the Newcastle area showed that with three conductors each 0·15 sq. in. in section, and with a pole spacing of 80 to 100 yards, the maximum permissible load on the poles was being approached unless excessive guying was resorted to. Unless, therefore, the present pressure of 20,000 volts is increased, the heavier conductors eventually required might result in the use of steel towers. Referring to the types of link insulators referred to in the papers, the G.E.C. design has the objection that the upper groove in the insulators forms a pocket in which water can collect during frost, and this results in cracking of the porcelain. It might happen that a group of insulators might fail in this way, and the insulators being tied together by the interlinked ironwork, it would be impossible Mr. Redman.

Mr. Redman. to see the fault from the ground. The problem had been put before English porcelain makers and they had re-designed the type with the upper groove so arranged that it would offer no lodgment to water. These insulators, under mechanical test, failed at 1½ tons, which suggests that the fastenings generally adopted are weaker than the insulators. Mr. Welbourn has mentioned the possible differences in capacity and charging current with the vertical arrangement of conductors. This feature has been considered, and for the lines in this district, at any rate, the departure from the triangular formation was found to be negligible.

Mr. Hunter. Mr. P. V. HUNTER: If the power supply companies in this district used as complicated schemes of connections as those shown in the paper, the diagrams on the control room walls would overflow on to the ceiling and the floor. The outstanding feature is the multiplicity of busbars, relays, isolating switches, etc., whereas in this district every attempt is made to reduce this apparatus to a minimum. In general each piece of apparatus has two automatic switches, but in the diagram there are, on the average, three or more and a larger proportion of isolating links. Mr. Welbourn has criticised the diagram showing the layout of a system, and it is certainly remarkable that in dealing with such large loads a large power company can treat their connections to their customers in the way shown in diagrams 11 and 12, in which there are no less than 9 tees with no serious effort towards automatic protection. I presume that the method of operation is to switch on to the other line as soon as trouble occurs on the working line, special arrangements being made for switching over. Such an arrangement requires a large, capable, and energetic staff of emergency switchmen and repairs engineers. In the North-East Coast district the whole development is on entirely different lines and every attempt is made to isolate faults automatically and carry out repairs in a routine manner, thus eliminating the personal element in the maintenance of supply. Mr. Welbourn commented on the fact that there was no balanced protective gear shown in the paper, but on diagram 6 there is a suggestion of the balanced protective system on the transformer automatic gear. I regret that the papers contain no wiring drawing of one of the sub-stations, as judging from the diagrams, this would be extremely complicated.

Mr. Anderson. Mr. J. A. ANDERSON: In regard to the network diagrams in Figs. 11 and 12, if any protective gear is used at all other than Merz-Price, a large proportion of the copper must be out of commission when running under normal conditions. On such a system, one could imagine that many of the relays would be "tied down." Under normal conditions, conductors of the same length and equally taut will swing synchronously, but during a snowstorm it has been found in practice that one wire may get more heavily coated than another, with the result that the wires may get blown against one another. In regard to the question of transmitting electrical energy from a coalfield to a large industrial area such as London, the commercial success of such an

undertaking would depend altogether on the load factor. A line 100 miles long to carry a load of 10,000 k.w. at 125,000 volts would approximately cost £800 per mile = £80,000. Allowing 12½ per cent. for interest, depreciation and repairs, the annual cost would be £10,000. Assuming a 40 per cent. load factor the number of units per annum would be 35 million. The cost per unit would be about 0·069d. Taking the cost of carrying coal at 3s. 6d. per ton for the 100 miles and assuming a ton of coal can produce 700 units, the cost per unit is only 0·06d. Mr. Anderson.

Mr. R. ROBINSON: In certain cases I have used hard rubber instead of porcelain with good results, but the rubber has disadvantages, one being that it snaps easily. Mr. Robinson.

Mr. G. L. PORTER: At present the Merz-Price system is limited to comparatively short lines, and the protection of some of the American lines extending for 100 miles would require a very special pilot cable, as the capacity current in the pilot of a 100-mile line would be a very serious problem. Mr. Porter.

Mr. A. H. LAW: With the flexible type of suspension a local gust of wind might start a swing which would be transmitted to other parts of the system where different conditions obtained, and consequently the wires would not be swinging in synchronism. Mr. Law.

Mr. A. L. E. DRUMMOND: That is so; I have seen both the poles and the wires swinging. Mr. Drummond.

Mr. W. R. MORTON: With reference to the question of protection against lightning, I do not think any mention has been made of a method of protection adopted by the Niagara, Lockport, and Ontario Power Company on their 60,000-volt transmission lines, and described by Mr. L. C. Nicholson.* Mr. Nicholson points out that the power arc following a flash-over is often the cause of the damage done to insulators. The device in question consists "of two metal rings concentric with the insulator, a lower one which is situated near the base being considerably larger in diameter than the insulator parts, and supported by three earthed metal strips attached to the pin; and an upper one somewhat larger than the neck of the insulator, just opposite the tie wire, suspended from the transmission cable and electrically connected with it." A glance at Fig. 11 of Messrs. Matthews and Wilkinson's paper will show that the flash-over takes place from the line wire to the pin at the base of the insulator. A power arc following a flash-over takes the same course, and the insulator is ruptured by the heat. This is by no means a natural path for an arc, and the two rings fitted by Mr. Nicholson serve the purpose of transferring the arc from the pin. They are far enough away from the surface of the porcelain to obviate the damaging of the insulator by the heat of the arc. The top ring takes the place of the line wire at one end of the arc and the burning of the tie wire is consequently obviated. It was found that, on a flash-over taking place, the arc instantly transferred to the two rings. Figures are given showing the Mr. Morton.

* *Proceedings of the American Institute of Electrical Engineers*, vol. 29, p. 241, 1910.

Mr. Morton. result of fitting these rings. In 1907, 59 insulators were disabled; in 1908, 139; in 1909 the rings were fitted and only one insulator was disabled. With reference to Mr. Welbourn's remarks on the use of aluminium, a consideration of the conditions of stress existing in a stretched wire will show that aluminium is only safe under certain conditions. A set of curves was recently worked out with the object of obtaining a reliable comparison between aluminium and copper of equal section, as they could be erected on the North-East Coast, *i.e.*, with 240 ft. spans; a 1/0 wire = 0·08245 sq. in. was selected. The worst conditions were assumed to be reached with a temperature of 22° F., a wind pressure of 17 lbs. per square foot, and a coating of ice equal in thickness to the radius of the wire. A safety factor of 2 was allowed. The ascertaining of the correct relation of stress and length of wire was done by plotting two curves. Any stress applied to a wire will elongate it according to the modulus of elasticity, and the relation between length and stress at any given temperature will be a straight line with a positive slope, *i.e.*, the length will increase with the stress. A stretched wire suspended between two fixed points follows closely the parabolic curve depending on span length and weight, which curve has a negative slope, *i.e.*, the length decreases as the tension increases. We are thus able to get two intersecting curves relating to the same wire, and the point of intersection being the only point (and therefore the only tension and length) that applies to the wire under both conditions, viz., both stressed and suspended, we are able to determine the tension and dip of a suspended wire at any given span-length and temperature. Curves were plotted for both aluminium and copper as mentioned. It was found that at the average summer temperature of 62° F. the dip required for the copper line was 1·40 ft. and the tension requisite to get this dip 1,630 lbs. For the same temperature the dip required for aluminium was 4·2 ft. and a tension of no more than 165 lbs., so that although aluminium has approximately half the tensile strength of copper, it must only be pulled up to about one-ninth the stress to get the same ultimate safety factor. This involves a larger dip and therefore a longer pole and longer cross-arms. This result is due to the relatively small proportion of the effective weight on the wire under worst conditions, which is due to the weight of the wire itself and to the low modulus of elasticity of aluminium. As the size of the wire increases, the portion of the effective weight due to ice and wind pressure decreases, because wind and ice pressure increase with the diameter, whereas the weight of the wire increases as the square of the diameter. Consequently the advantage which copper has on account of its high specific gravity decreases in larger sizes. By making a number of trial curves it was found that the smallest size that would appear to be worth while erecting aluminium for is that equivalent in conductivity to a 0·1 sq. in. copper, and that the longest span used should not exceed 45 yards. In view of the cost of the extra poles required and the increasing cost of wayleaves, the economical use of aluminium

appears to be limited to the transmission of large amounts of power over short distances. Another point to be remembered is the superior value of scrap copper as compared with that of aluminium. Mr. Morton.

Discussion before the Manchester Local Section, January 31, 1911.

Mr. J. S. Peck: Mr. Taylor's paper seems to me to be of special interest in that it gives us a general idea of the magnitude of the problems involved in long-distance transmission. He treats of everything in a general way, from the design of towers and insulators to the cost and selling price of electricity. I do not agree altogether with some of the statements in the earlier part of the paper. I think he is a little confused in his ideas of capacity and inductive effects. Mr. Matthews' paper goes more into details regarding the construction of insulators and towers, and is an extremely valuable contribution. There are many points of interest in these papers. Some of them have been thoroughly discussed before the American Institute of Electrical Engineers and practically settled, while others are still being discussed by engineers who are interested in this subject. Mr. Taylor recommends split conductors. Now, with this arrangement it is necessary to transpose the wires carefully, otherwise the distribution of current between them may be very unequal, due to what may be termed skin effect. One of the sources of trouble in connection with transmission systems of 30,000 to 40,000 volts was that large birds got across the wires and caused short circuits. I notice in neither of the papers is this trouble mentioned, presumably due to the fact that at these very high voltages the spacing of the wires is too great for birds to span. Mr. Peck.

Mr. W. Cramp: Like most engineers in this country, I have had little experience of high-tension transmission, and therefore while I am grateful to the authors for giving us the information contained in the papers. I am unable to offer any useful criticism. I should, however, like further explanation of some of the points they have raised. The papers are more or less complementary in the ground they cover. For instance, in one there is a most extraordinary statement concerning capacity and resistance which I puzzled over for a long time. It occurs at the bottom of page 571 of Mr. Matthews' paper in the following words: "The charging current varies with the electrostatic capacity and the resistance varies inversely with the electrostatic capacity." I could not imagine what was meant by that sentence, until I found in Mr. Taylor's paper a clear explanation of what it purports to convey. On page 562 of Mr. Matthews' paper it is stated that "a pressure of 200,000 volts is now considered to be within the range of practicability." I should like to know where such a system as that is proposed, for Mr. Peck in his address as chairman mentioned about 120,000 volts as the limit that insulators would withstand satisfactorily, and there seems to be a very large margin between 120,000 and 200,000. Mr. Cramp.

Mr. Cramp. In connection with this limit, surely the question arises as to whether that which is satisfactory in the United States can be so in England. I think that on account of difference in climatic conditions the number of insulators to be placed in series would be very different in various countries. Though the papers complement one another, as previously stated, they are not always in agreement. For instance, on page 567 of Mr. Matthews' paper we are told that the poles are set at distances from 300 ft. to 350 ft. apart. In Mr. Taylor's paper, on page 527, we are told that the limit, instead of being 350 ft., is 750 ft.

There is an interesting curve in Fig. 13 in Mr. Matthews' paper showing the corona discharge losses. I do not know what is meant by corona losses in this case. According to the slide shown it seems like a discharge such as one gets from a concentrated leakage. The curve, Fig. 13, is very interesting as determining the point at which the discharge grows very rapidly. We have, for instance, a bend in the curve at 120,000 volts. Now, I want to ask the authors whether it is desirable, or usual, so to design the distance between wires as to keep to the left of that point marked 120,000 volts in Fig, 13, or whether it is not usual to use very much shorter distances than that. What limit would Mr. Matthews advise as admissible for corona losses?

Of course, the test of what engineers have achieved in such systems as these, is the accuracy with which new schemes can be calculated. Of this there is nothing in Mr. Matthews' pages, but on pages 514 and 541 of Mr. Taylor's paper there are comparative systems of calculation which are extremely interesting. And while in connection with pages 513 and 514 certain details of calculation are given ; on page 541 there are several items missing which render it impossible to compare the two systems. For instance, we take on page 513 the self-induction of one wire, and there is an approximate formula given for its computation. On page 541 the value of the reactance is presumably at 40 periods, but there is no information given as to how the coefficient of self-induction has been obtained. I should like to know whether the formula given on page 513 has been used, or whether it is to be obtained by some other means. Also on page 541 the letter b is used to signify "Capacity susceptance per mile of two parallel conductors for a frequency of one cycle per second," while later on the letter B signifies "Total capacity susceptance." If I understand the meaning of that term "susceptance," I should say that it was in this case misused, and that in any case the frequency f which appears in the formula is either American practice, or it is founded upon a new definition of susceptance. Again, on page 542 the letter t occurs again and again, but no meaning has been assigned to it. Lastly, throughout the calculations the author has made use of the capacity current. He does not appear to calculate the joint reactance due to capacity and self-induction and take that into account in his pressure-drop figures. I wish to add that the ingenious device of flexible supports put forward by Messrs. Matthews and Wilkinson is a great improvement on previous four-footed structures and should materially cheapen the system.

Mr. Fleming.

Mr. A. P. M. FLEMING: I should like to know the opinion of the authors as to the feasibility of employing on really high-voltage systems, one of the three line conductors, suitably earthed, in place of the earthed protecting wire ordinarily supported on the highest point of the pole construction. While this arrangement would upset the symmetry of the electrostatic conditions of the three lines, and would considerably increase the stress on the insulators supporting the two insulated lines, the total increase in cost involved in using insulators of the suspension type suitable for the increase in stress would be comparatively small, and would be offset by the saving in cost and erection of the special earthed wire and the insulators on the earthed line. There does not seem to be any serious electrical objection to such an arrangement, and the recent improvements brought about by the adoption of the "suspension," in place of the "pin-supported" type of insulator, would appear to afford sufficient safeguard against risk of line failure due to the increased electrostatic stresses.

Mr. Faye-Hansen.

Mr. K. FAYE-HANSEN: There are several points in Mr. Taylor's paper on which I should like further information. On page 512 he states that "the effect on the line caused by a flash-over of the lightning arresters may cause a heavy disturbance on the whole system, since the reaction set up tends to increase the current on the line in proportion to the square of its original value." I do not quite understand the meaning of this sentence, and should like to know if it is the effect of suddenly interrupting the current in the lightning arrester which is referred to. This interruption of current may cause a voltage rise proportional to its own value, and for a given power the effect of this will be smaller the higher the voltage, the percentage increase being inversely proportional to the square of the voltage. I have only been able to make out the regulation diagram Fig. 1 by assuming three printers' errors, namely, that the voltage of the generating station is E_g, the voltage of the receiving station E_a, and the resistance drop due to power component O_b. On page 520, 522, and 523, the author refers to the use of oil-switch bushings as primary for the series transformers by the General Electric Company's Schenectady Works. This practice has also been adopted by the Westinghouse Company for high-voltage switches. It can, however, only be used on fairly large systems, as the characteristic of the series transformers for small currents (below, say, 100 amperes) becomes too bad. For this bushing type of construction the condenser-type terminals as used by the Westinghouse Company for 60,000 volts and higher, are specially favourable, as a smaller diameter of the iron ring of the series transformers can be used than with any other terminal construction. I wonder if the statement on page 521 "that three 6,000-k.w. transformers are used with a 12,500-k.v.a. generator" is not a misprint. I agree with the author that it is good practice to arrange three single-phase transformers or one polyphase transformer for each generator, but having the same kilovolt-ampere capacity as the generator independent of the size. I should like to see a sketch added to the descrip-

Mr. Faye-Hansen. tion of the method of connecting each piece of the suspension-type insulator together. What I am specially interested in is the arrangement to prevent the porcelains from being subjected to mechanical stresses other than compression. Regarding the electrical calculation of lines, it would be interesting to know which tables are referred to on page 541. Are these published tables based on tests or on the more theoretical formula given on pages 513 and 514? Under the heading "Electrical Connections" the author does not always make clear whether he means the connections of the transformers or of the lines. It is, of course, possible to connect the transformers in star on the high-tension side without grounding the neutral either direct or through a resistance, and from the operating point of view the results are the same as with delta-connected transformers. The transformers themselves, however, will be somewhat cheaper, and have higher efficiencies, than if connected in delta. It is also possible to connect the transformers in delta and produce artificially a neutral (for instance, by an interconnected star balancer) for earthing purposes, though this, as a general rule, would be a rather expensive procedure; and the conditions for the lines are in this case the same as if star-connected transformers with grounded neutrals are used.

The author states that, with the neutral grounded, the insulators need only be 57 per cent. of those used on an ungrounded line. Though this is theoretically correct when the grounding is perfect, it no longer holds good when the neutral is connected to earth through a resistance, as in case of a fault to earth on one phase, the two other phases may for a short time be subjected to a voltage to earth nearly equal to the full-line voltage. The author seems to favour the use of delta connections of the transformers to start with, the transformers and insulators being designed for connecting in star later, with the neutral grounded, a higher voltage being then obtained without any other alteration. I cannot see sufficient reason why the transformer should not be connected in star and the neutral earthed from the commencement. The capital outlay is the same, and for the first years of operation the regulation is improved and the copper loss reduced. The author states that, in his opinion, in future, provision of reserve plant at various receiving stations will not be made. If, however, we look at Fig. 24, p. 557, we find that, for low load-factors, the price of power delivered from steam plants is lower than for hydro-electric plants and transmission lines, and this will, due to the higher capital outlay for the latter, nearly always be the case. Though the hydro-electric plant should be so designed that from the point of view of continuous supply reserve plant at the receiving stations is not required, it will, however, often be advisable, due to the economy thereby obtained, to have steam plant at some large receiving stations to take the peak load, and at the same time to form a reserve.

Mr. Malpas. Mr. A. E. MALPAS: Taking Mr. Taylor's paper first, and referring to the corona effect mentioned on page 512, I believe some experiments have been made on the use of a cable built up on a thin copper con-

ductor wound round a hemp core. With regard to the use of split conductors, this system has been recently adopted in the case of a large installation supplying approximately 20,000-H.P. at 60,000 volts from a point on the River Jucar to Madrid, over 300 kilometres away. In this case the two sets of wires run on the same posts. It seems, however, preferable to run the duplicate line on independent posts for convenience in making repairs, as in the event of trouble both lines would probably have to be shut down. For the tables given on page 580 to be of any value, the scantlings of of the posts should have been given. I trust the author will be able to give in his reply further details of the actual posts used for the purposes of these tests. The remark made at the bottom of page 544 is of value, as in the event of a burn-out with one of the transformers in delta connection, the other two could be so coupled up as to carry on a work at a correspondingly reduced load. Mr. Ma'pas.

Referring to Mr. Matthews' paper, in the later Continental practice the overhead ground wire does not appear to be in use. At least, it has not been used either in the case previously mentioned, or in the case of another quite recent installation made for supplying 15,000 H.P. to Madrid at 50,000 volts, from a point on the River Tagus, 75 kilometres away. From the mechanical point of view, I certainly agree with the authors of the paper that this ground would be of considerable advantage. Referring to the new flexible tower construction, this construction was followed in the case of the Bolarque installation just mentioned. The towers or posts used on this line were of extremely light construction, but have in practice proved very satisfactory. I was pleased to see the slide shown by Mr. Matthews illustrating the earthing device adopted at railway crossings, as it is the first time I have seen any mention of it; in fact, I thought I had invented the system myself in the case of a 5,000-volt transmission system, with which I was connected, for some mines in the south of Spain. I am of the opinion that this device should be more largely used wherever any traffic is to be expected, or even where crossing the more unfrequented roads.

Mr. J. Foster: I would remind Mr. Cramp that formulæ and data upon which the design of high-tension transmission lines could be based have been available for several years, but nothing has as yet been done in this country with regard to really high-tension transmission. The real cause of our backwardness is not lack of mathematical data; in fact, transmission lines have been built in the United States and on the Continent before formulæ and data were available. Probably when we do build high-tension lines in this country we shall follow the same procedure, and after everything has been brought to a successful conclusion, no doubt some mathematically inclined person, possibly Mr. Cramp himself, will come along and explain how it has all been done. What we lack is not data and information, but initiative and moral courage. The idea held by many engineers that high-tension transmission could never be employed in this country because of the Mr. Foster.

Mr. Foster. absence of great water-powers overlooks the fact that there are other sources of cheap power, notably surplus blast-furnace gas and surplus coke-oven gas. In this country about 10,000,000 or 11,000,000 tons of pig iron are produced per annum, and with large economical gas engines, the surplus of power, available after supplying all the needs of the blast furnaces, is between 1,000,000 and 1,500,000 B.H.P. continuously. In addition there is a large amount of power available from coke-oven gases, and by means of suitable transmission schemes these large and at present waste powers could be to a large extent beneficially utilised.

Mr. Lustgarten. Mr. J. LUSTGARTEN: I should like to draw attention to the phenomena of corona or glow around the transmission wire. One of the limiting factors in high-tension transmission is the electric strength of the air itself. Given a wire of any diameter at a fixed distance from a similar wire in a single-phase transmission, there is a certain voltage at which a glow appears, and at this stage the air is said to be "broken down." If the diameter of the wires could be increased, it would be necessary to raise the voltage in order to produce a glow. Conversely, for a fixed voltage, the limiting diameter of the wire can be deduced. If the electrostatic field intensity or stress at the surface of the wire be calculated, it is found that for a wire of, say, 0·1 cm. diameter the intensity is 80 kilovolts per centimetre, and for a larger wire of 0·5 cm. the value is 50 kilovolts per centimetre, and if you still further increase the diameter of the wire the intensity of the field diminishes. This is the same for direct- or alternating-current difference of potential. These values are obtained in the spark discharges between two equal spheres. The maximum electric intensity at the surface of small spheres at the moment of breakdown or discharge is about 60 kilovolts per centimetre, and of very large spheres about 30 kilovolts per centimetre. With the object of obtaining some clue as to the reason we obtain a different strength of field (a different intensity at the moment the corona appears with small wires as against large wires), I have, in the course of an investigation, not yet completed, been carrying out some experiments on spark discharge between unequal spheres, and with a sphere of 1 in. in diameter, and another of 2 in. in diameter, the maximum electric intensity at the moment of discharge for the smaller was found to be 45 kilovolts per centimetre, and for the larger sphere 30 kilovolts per centimetre. We shall eventually find that the disruptive strength of air expressed as an electric intensity (or potential gradient) will be constant, but at present there is no explanation for the different breakdown values with decreasing diameter of wires or of spheres. Steinmetz has suggested that a zone of condensed air contiguous to the surface of the wire, having an increased pressure due to molecular attraction and depending on the curvature of the wire, would account for the above discrepancies in the breakdown values of maximum electric intensity, but I cannot agree with this, as the attraction will only be at molecular distance, and therefore should be independent of the sizes of the wires.

Mr Lustgarten.

In Fig. 13 in Mr. Matthews' paper, it will be noticed that the corona having appeared at a certain point, the curve bends suddenly upwards. In plotting the sparking voltages corresponding to the distance between two equal or unequal spheres at a certain stage, the curve takes a sudden bend upwards; but at this kink there exists more than a glow, it is a distinct brush discharge, the glow or corona having appeared at a smaller sparking distance. With the appearance of this brush a larger voltage is required to cause a discharge across a gap probably because of the loss which is taking place in the brush, or what is the same thing, because of the energy required to produce and maintain the ionisation in the brush discharge. I am unable to agree with Mr. Matthews' statement made on page 571 with regard to the effect of the percentage of moisture of atmospheric air on the corona loss. My own experimental observations on the sparking distance between spheres with different states of humidity of the air, even in dense foggy weather, give no difference for the sparking voltages, or the point at which the glow appears. Further, some recent experiments have been made by Dr. Whitehead in America * in order to determine the voltage at which the corona appears, and this investigation shows that it is independent of moisture content of the air.

In Mr. Taylor's paper, in the section on suspension-type insulators, the statement that "a flat plain disc has a greater electrostatic capacity than a similar disc with concentric petticoats on the under surface" requires some modification. With the same thickness of porcelain between the same electrodes in the two cases, the electrostatic capacity must be the same and the voltage at which corona starts, both on the electrodes and on the porcelain, must also be the same. With increase of voltage the corona on the petticoated disc is forced downwards, and thus its effect as a condenser, or conducting area, is diminished. This action, together with an increase in the arcing distance (especially if the petticoats are long), requires a greater sparking voltage than in the case of the flat plain disc.

Mr. Mallinson.

Mr. A. B. Mallinson (*communicated*): I would like to have some further information from the authors on the following points. In both papers a continuous earth wire above the live wire is spoken of as now being almost a universal practice. In Mr. Taylor's paper such earth wires are shown on the pole-lines for two sets of transmission wires, but the single pole lines do not appear to have been designed with this in view. Similarly, in the paper by Messrs. Matthews and Wilkinson no such arrangement is shown provided for in the single circuit lines on Fig. 2 and Fig. 3. This would make it appear as though the use of an overhead earth line is not generally adopted. Overhead earth wires of barbed wire were erected in several instances for high-pressure lines in this country some years ago, but, as far as I am aware, have been dropped because of the short life due to corrosion. Presumably, for this reason the stout earth wire is now recommended. No particular note is made

* *Proceedings of the American Institute of Electrical Engineers*, vol. 29, p. 1059, 1910.

Mr. Mallinson.

in either paper on climatic conditions as affecting surface leakage. Have the authors heard of difficulties in this manner with these extra high-tension transmission lines? I note also that with the suspension type of insulator the same insulators are apparently used for the anchor posts. This will pull the insulator out of the vertical and expose the petticoat underneath it to moisture. Has it been found necessary to increase the number of insulators in series on the anchor posts on account of this? Aluminium wire has been mentioned very little by either author, and I should like to know whether it is yet being used to any extent in the United States for transmission work, and if so whether any difficulties have been found with it due to the sag increasing when the wire stretches as a result of age. In both papers an illustration is given of a typical 110,000-volt line with two circuits each in a common vertical plane. Have any such transmission lines been run in tropical countries where the rainfall during the wet season is extremely heavy, and if so, has any trouble been found due to continuous dripping of water from the wire on the top insulator on to the earthed framework or wire immediately below it?

Professor Marchant.

Professor E. W. MARCHANT (*communicated*): Mr. Taylor's paper is one of great interest and importance, as he is able to give practical information on high-tension transmission. The problem of transmitting energy over long distances is one of great importance in a country like America, where there is ample water-power, and the distances to be covered are much greater than in this country. Over here the question of wayleaves is fundamental, and I should like to reiterate the hope I expressed in the discussion on the paper by Mr. Watson and myself, read last session, that some information may be forthcoming on this matter. Dealing first with the subject of transmission in general, it is, I think, remarkable that no attempt has been made hitherto to apply the results worked out, by Steinmetz (in his book on "Alternating-current Phenomena"), for "wave" transmission. Steinmetz shows that it is possible so to adjust the line constants that the pressure at the transmitting and receiving ends of a line shall be the same. For a short line the extra capacity and inductance that would require to be introduced to give a "wave" transmission would be too great, but it does not seem unlikely that such a scheme would be workable for such transmissions as are described in the paper by Mr. Taylor and Messrs. Borlase Matthews and Wilkinson. Coming next to some details in Mr. Taylor's paper, I should like to refer first to the use of wooden pins for insulators. In nearly every station which I visited in America, with the possible exception of Ogden, Utah, wooden pins were being replaced as rapidly as possible by metal pins, the trouble due to digestion of the wooden pin by brush discharge from the thread of the screw in the insulator being most serious. On page 537 Mr. Taylor states that "corona has the effect of reducing the effective resistance and increasing the line loss." This surely is a mistake, as the production of the corona absorbs a considerable amount of power and

has the same effect as increasing the line resistance. While writing on this subject, I should like to refer to a statement on page 572 in Messrs. Matthews and Wilkinson's paper, that the working of a line slightly below the critical point may act as a safety valve for lightning discharges. This is a very dangerous method of protection, because of the likelihood of "flashing over" between the lines. I remember very well when walking down the Black Canyon, close to the Shoshone Falls Station of the Central Colorado Power Company, being suddenly started by a brilliant flash 2 or 3 miles away, due to a "flash-over" between the lines (which were then working at 90,000 volts), due, I presume, to a lightning surge or something of that kind. The factor of safety against corona effect (allowing for altitudes) on that line is about 1·34, and this "flash-over" seemed to me an indication that the factor of safety was really a little lower than was consistent with entirely satisfactory working. Small particles of dust and dirt on a line working under these conditions will produce a brush discharge, and have the effect of ionising the air and thus rendering a flash-over more likely. With reference to the statements made on page 547, that the present practice of transmission engineers is not to transpose circuits, I should like to point out that at the Great Western Power Company's transmission in California, which is the best design I have seen, transposition towers have been introduced about every 4 miles, and unless this is done, transpositions of the telephone wires themselves, whether they are on the towers or in the neighbourhood of the line, will not completely eliminate induction effects. It is interesting to notice that the costs given on page 550 are not as low as those which Mr. Ferranti has indicated as being possible (*i.e.*, ⅛d. per unit), for gas engines working on a good load factor. The problem of the construction of a line which will be thoroughly reliable under all conditions can hardly be considered to have been solved, if one can judge from experience, on the long-distance transmissions on the west coast of America. I have already referred to the flash-over on the 90,000-volt line on the line of the Central Colorado Power Company, but, even at Island Bar, during the short time I spent in the station, there were two or three short circuits (occurring at some point on the transmission line) which had the effect of operating the relief valves, thus causing the surge pipe (which protected the pipe line from water-hammer) to overflow. In San Francisco the stoppage of the tramcars for 10 and 20 minutes appeared a very common occurrence. There is very little doubt, of course, that, as time goes on, the reliability of such transmission schemes will improve. Professor Marchant.

Discussion before the Yorkshire Local Section, February 15, 1911.

Mr. W. B. Woodhouse: We have listened to two very interesting papers on this subject of overhead transmission lines, but they both deal with lines of such length and voltages as we are not likely to require in Mr. Woodhouse.

Mr. Woodhouse.

this country. As, however, the mechanical construction of an overhead line has to satisfy the same conditions, whatever the voltage may be, we may consider some part of the papers as having a direct bearing on methods of construction in such a country as our own. The real difficulties of overhead line construction in densely populated countries are not touched on in Messrs. Matthews and Wilkinson's paper. Frequent road crossings, deviations to avoid the land of owners who will not grant wayleaves, railway and telegraph crossings, all present greater difficulties than the design of a cross-country line, where angles can be avoided and obstructions are few. The question of the most economical span is easily settled in a thinly populated country, and in such cases there is little doubt that long spans and high towers are the best, but it is rather an exaggeration to say that wooden poles are practically a thing of the past. It all depends on local conditions. With regard to the corona effect, this has an important bearing on the distance to be kept between wires. The effect of climate, dust, and air pressure on the critical voltage is very considerable. Professor Ryan states that the minimum critical voltage gradient is about 3,000 volts per inch, therefore the practice advocated in both papers of one foot between wires per 10,000 volts is on the safe side, though it is a rough and ready rule; the possible contact of swinging wires is the real limit in most cases, as good pressure regulation requires the distance between wires to be kept small. The adoption of split conductors to reduce the impedance, advocated by Mr. Taylor, seems the first step towards a network of interconnected lines such as is used in this country for 10,000-volt work. The most difficult problem on lines transmitting large amounts of energy is that of control and switching; operation difficulties increase very rapidly with an increase of current, and greater security may often be obtained by increasing the voltage and decreasing the current.

Mr. Matthews' distinction between "rigid" and "flexible" towers is one that I do not quite understand, since all structures are flexible; early construction work certainly did not err on the side of rigidity. The distinction that I think he intends to convey is that a flexible tower is one which is more flexible in the direction of the line than at right angles to it. The benefit of a structure of this kind is apparent when the stresses are considered for wires firmly fixed to the insulators, but with the adoption of the suspension insulator (see the analysis of the stress set up by breakage of wires in Mr. A. P. Trotter's classical paper of 1907)* the need for a special consideration of flexibility disappears. The use of suspension insulators seems to be a step in the right direction, but we have not yet come to the final type of insulator. Many of the designs shown are much too heavy, and mechanically defective in that if the insulator breaks the line will fall; these are serious faults. I have for some years used suspension insulators for securing safety in road crossings and found them satisfactory.† The

* *Proceedings of the Institution of Civil Engineers*, vol. 169, p. 183, 1906–1907.
† *Journal of the Institution of Electrical Engineers*, vol. 44, p. 813, 1910.

best connection of 3-phase transformers at the ends of a transmission line, dealt with by Mr. Taylor, is a subject of considerable interest; there seems to be a balance of advantages in favour of delta-star connections, more particularly on account of the possible surges due to intermittent faults. I should like the authors' views on this, as experience is badly wanted. Mr. Woodhouse.

Mr. T. H. CHURTON: The question of the overhead transmission of electrical energy at high pressure is one of growing importance, in that it is intimately associated with the cheapening of electric power supply. Popular prejudice must be overcome and public opinion created that will prevail upon the authorities to grant increased facilities for the construction of overhead lines. The powers of veto which local authorities now enjoy should be modified, and that result may be brought about by informing ourselves upon what is being done elsewhere and what may be done here, and by educating the public, each within his own sphere of influence. In this connection, I shall be glad if Mr. Snell or Mr. Matthews can inform us of the relative cost of an overhead line and an underground cable working at the same pressure and of the same kilowatt capacity, and under otherwise similar conditions. The principal advantage of overhead lines as compared with underground cables appears to be that of cheapness, but to make the comparison fair the cost of maintenance of the two systems should, of course, be taken into account. One of the characteristic features of electric power lines in America is that they are almost all carried on wooden poles, generally untreated and roughly finished. The main lines, especially those of very high pressure, are, however, usually supported on steel towers. With regard to the spacing of the wires, I was surprised to notice how comparatively close together the lines of the Yorkshire Electric Power Company are, and though this may be an advantage as regards inductive drop on the line, there must be, one would think, considerably greater risk of short-circuits. I should like to ask whether any trouble has been experienced with the stretching of the lines of such an enormous span as 4,000 ft. mentioned by Mr. Matthews. With regard to lightning, I may mention that when in Montreal last summer a most terrific lightning storm was experienced, and which was said to have been the worst within living memory. The city is supplied by power from three separate hydro-electric stations at distances varying, I believe, from 30 to 60 miles. The power lines were struck fifteen times during the storm. On twelve occasions the horn lightning-arresters prevented damage; on two occasions part of the town was thrown into darkness momentarily, and on another occasion for about fifteen minutes, before the fault could be located and the supply resumed. I mention this as an instance of what has happened under conditions of the greatest severity. I was informed that power lines operating at 100,000 and 110,000 volts did not suffer from lightning nearly so much as the lines operating at lower voltages; the explanation being, I believe, that the high-voltage Mr. Churton.

Mr. Churton. lines are necessarily so well insulated. For this reason one would think that it would certainly pay to insulate lines in the same manner, whether to be used for the higher pressure or not, if only as a safeguard against the risk of breakdown due to lightning.

Mr. Welbourn. Mr. B. WELBOURN: I am rather handicapped in taking part in this discussion as, having already spoken in London, it makes it a little difficult to avoid covering the same ground. One point, however, which I touched on in London, and which I should like to refer to again, is the life of the poles. Both the authors give the average life of the pole as 12 years. I think it is quite clear that that figure applies only to untreated poles—poles that are cut down and put up *in situ*. I have been making inquiries as to the probable life to be expected in England, and I think there is good reason to believe that properly creosoted poles will have a life of 30 years, and it may be that 50 years may be got out of them. I am inclined to think that, with English conditions, we shall have a much longer life with wooden poles than steel towers. With regard to the life of steel towers in this country we have had very little experience. It would be helpful if the railway engineers would tell us something on this matter. From what we know of the pitting of steel tramway poles at the ground line I think we should be well advised to avoid the use of flexible steel towers in this country until we know more about their behaviour in the English climate. With regard to the Chairman's remarks as to the comparative costs of underground cable transmission and overhead construction, I can give you some figures for the very best pole line construction in this country at the present time: A single-circuit 20,000-volt 3-phase line transmitting 5,000 k.v.a. costs £800 per mile. A double-circuit line for 10,000 k.v.a. would cost about £1,250 per mile. With underground cables, where it would be necessary to put in 20,000-volt 3-phase feeders, and including the cost of street work, it would run to about £3,500 per mile forward; each cable would carry about 5,000 k.v.a. regularly. I would like to have heard Mr. Woodhouse say whether he uses the overhead ground wire which is referred to in the papers. The general English practice is not to use it except underneath the power wires, and there it is sometimes used as a catenary wire to support lead-covered telephone and pilot wires, and is also used for grounding the ironwork in the event of a fault occurring on an insulator. I would like to ask the authors if they will tell us how they carry out the grounding. The inference from the paper is that they rely on the foundations of the steel towers for this. Those who have tackled this question of earthing find it an extremely difficult problem in England. I would ask the authors what special methods are adopted for getting a really good earth that will transmit current until the breakers operate and cut the line dead in the event of a fault occurring. Mr. Matthews referred to the equal accumulation of ice and snow on both aluminium, copper, and steel wires. I am told that there was some doubt on that point even amongst the engineers from the other side of the water. I hope, however, to

have some figures on this point shortly. One practical point came to my notice in a letter from Canada regarding the flashing-over on insulators. The practice appears to be to put a long metal sleeve over the line wire so that when the flashing-over occurs the burning takes place on the sleeve and binding-in wire and not on the line wire. Mr. Welbourn.

Mr. E. H. FARRAND: With reference to the remarks of the previous speaker, I would like to say as a Post Office engineer that my experience is that instead of the life of poles in England being 12 years, we can depend in favourable circumstances on 30 to 35 years, and in unfavourable circumstances something like 20 years' life. This applies to creosoted poles. In many cases we have taken poles down that have been in since the early days of Post Office telegraphy in 1872 which have been perfectly sound. The difficulty appears to be in England that if poles are put in sand or porous material they rapidly deteriorate in the ground because the creosote runs out and is absorbed by the ground; on the other hand, if they are put in wet or clayey ground they stand indefinitely, as the creosote runs down from the top of the pole and forms a bath at the foot. With regard to Mr. Welbourn's point as to the accumulation of snow on wires, I gather from the papers that the authors are of the opinion that snow accumulates very much the same on all classes of wire. Apparently they are only dealing with aluminium and copper, and I have had no experience of aluminium, but I have with copper and iron, which would be a parallel case to that of steel and copper. We have found that there is a great deal of accumulation on both iron and copper wires. With copper wire, however, the accumulation begins very much earlier than with steel, and it begins to fall off very much earlier also. On the occasion of the storm in February, 1900, I noticed copper wire accumulate snow to the extent of 3 in. in diameter in a few minutes, whereas the snow on the iron wire was only ½ in. to 1 in. thick at first, although the iron wire was the thicker, the gauges being, copper, 150 lbs. per mile; iron, 400 lbs. per mile. After the lapse of a short time it was impossible to distinguish which wires were copper and which iron, all having apparently accumulated snow to the same diameter. Mr. Farrand.

Professor G. D. A. PARR: I would like to ask the author whether the 7,000-k.v.a. load mentioned at the top of page 521 of Mr. Taylor's paper is entirely an "apparent" load. I take it that this load would be due entirely to the inductiveness of the line, and therefore presumably the current would lag nearly 90° behind the pressure and be almost all wattless. With regard to the type of suspension insulator shown, I should like to know whether there is not a considerable amount of chafing due to the action of the wind in drawing the cable backwards and forwards through the sleeve, as this seems to me a possible effect. Professor Parr.

Mr. F. THURSFIELD: With reference to the diagrams shown in the early part of the paper, what struck me was the great number of switches provided for different cross-connections, etc. If we take, Mr. Thursfield.

Mr. Thursfield.

for example, Fig. 9 on page 523, there are no less than five switches in series on each incoming line before getting into the sub-station. Having regard to the difficulty of constructing a switch for 100,000 volts, it seems undesirable to provide five in series, especially when we notice that according to this diagram the two switches nearest to the sub-station cannot be attended to without shutting down the whole sub-station. I suppose some other provision must be made, but that would appear to involve a sixth switch. The tables at the end respecting the cost do not give the capacity of the station in question. But it seems from the tables that it is possible to get at it, for in column A of Table IV. we have the load factor and in column E the millions of kilowatt-hours. Presumably this column gives the millions of kilowatt-hours per annum. If so, the maximum load can be obtained, and as the author states that no allowance is made for spare plant, the maximum load is the capacity of the station, which works out at 37,500 k.w. Turning to Table II., it is interesting to see what the capital cost of one of these large water-power stations is. By adding together the first four items, viz., dams, pipe lines and tunnels, power station equipment, and buildings, we get a figure of £2,220,000, which works out at £60 per kilowatt for the power station alone. Some reduction may possibly be needed for spare plant in this case, but evidently the problem of supplying power on a large scale in this country is a much more simple matter, where we can provide generating stations for £12 or £15 per kilowatt. Ten per cent. interest on £60 per kilowatt comes to 0·4d. per unit, with a 0·4 load factor. In this country the corresponding charge would be perhaps a tenth of a penny, leaving 0·3d. to cover fuel and other extra working costs. Whatever the capacity of the power station is, it is clear that two-thirds of the whole annual expenditure is interest on the power-station plant only.

Dr. Pohl.

Dr. R. POHL: On page 537 Mr. Taylor states as follows: "Each piece or unit of the insulator has a dry flash-over of about 90,000 volts when used individually, but as the distance between units is less than the equivalent air-gap for the flash-over of 1 unit, the flash-over of the complete insulator is less than the sum of each unit taken separately." This explanation for the well-known fact that each added unit raises less than proportionately the flash-over voltage of the combination does not appear to me to be the correct one. If it were, it would be possible to obtain with four units only the result which according to the table on page 538 is now obtained by 6 units, simply by increasing the distance between units, *i.e.*, by lengthening the support. One may safely assume that the makers of the insulators carried out experiments in this direction before finally deciding on the form of the units and on the distance between them. Quite generally, for any class of insulating material the breakdown voltage per unit of length decreases with an increase of the total length subjected to the test, and the reasons why this should be so are well understood. They lie primarily in the unequal distribution of the electrostatic stresses. I believe in the case

of insulators of the kind under consideration the ionisation of the air due to silent discharges which precede the actual flash-over is of considerable importance in determining the flash-over voltage. There is one other point on which I disagree with Mr. Taylor. He states on page 510 that it is the complication of the high-voltage direct-current system which stands in the way of its universal adoption. To my mind, if there is a point which favourably distinguishes the Thury constant-current system more than any other it is its extreme simplicity. The true reasons why this system has not made more rapid progress appear to me the greater cost of the generating plant, which balances the proportionately large saving in the transmission line, except in cases where the expense of the latter plays a very great part in the total cost of the scheme, and secondly the constancy of the C^2R losses. With regard to the first point the advance in the design of direct-current machinery has solved the problem of constructing large high-tension dynamos at reasonable cost, and to the C^2R losses we must surely get reconciled when we hear from Mr. Taylor, in connection with 3-phase lines, of leakage and corona losses amounting to 1 k.w. per mile, and of charging currents corresponding to 20,000 k.v.a. It seems to me, after reading these papers, that the prospects of the Thury system for long distance transmission are even brighter than I had previously thought them to be. Dr. Pohl.

Mr. G. GILLETT: I would like to ask whether the steel towers are made up on the job, or are they made at the factory and transported as a whole? In comparing the cost of these with wooden poles, I was struck with the short life of 12 years which is given for the latter. My experience is such that I should be inclined to put the average at quite seven years more, which would make a considerable difference in the calculations if the latter figure was adopted. On page 529 of Mr. Taylor's paper I note with surprise that it is the practice to run telephone circuits on the same towers carrying the high-tension circuits. It appears to me that in this country we should have great difficulty in getting men to attend to those circuits. The practice in this country is to run covered telephone wires when crossing power circuits. On page 547 it is mentioned that the present practice of engineers is not to transpose, which I think refers to the telephone circuit. I do not quite see what is done to eliminate induction derived from the power circuit. Is only one transposition made for the whole length, or none at all? Mr. Gillett.

Messrs. R. BORLASE MATTHEWS and C. T. WILKINSON (*in reply*): In endeavouring to deal with the very valuable remarks of the members of this Institution, the authors are met by the difficulty that almost all the speakers have commented on both the papers by Mr. Taylor and themselves, and in doing so have frequently changed rapidly from the one to the other. After sifting out the points to which it is essential a reply should be made, a further difficulty is encountered in that a reply to be of any value would have to be of considerable length. The experience of the authors during the last few years—one of whom has Messrs. Matthews & Wilkinson.

Messrs. Matthews & Wilkinson.

specialised entirely on this subject—has led to the accumulation of an enormous amount of important data, but exigencies of space prohibit the dealing with those points brought up by the various speakers which are not strictly within the range covered by this paper. For example, wood poles, steel towers, insulators, conductors, etc., have each been considered especially from the point of view of extra-high-tension work, and not for conditions below about 60,000 volts. The very large number of lines referred to on page 567, aggregating nearly two hundred, have, of course, included a great variety of conditions—varying from the severe cold of Canada and the heavy sleet storm districts of the United States, to the special circumstances of tropical countries. Conditions which embrace both the serious mechanical difficulties in crossing mountainous countries, and the troubles of transport and labour in foreign and partially civilised countries, not to omit mention of the still greater obstructions, which—as Mr. Woodhouse so feelingly puts it—are found in the still more densely populated districts where antagonistic vested interests have to be pacified, and where the crossing of rivers, roads, canals, harbours, and other similar features of civilisation has to be negotiated. Then again there are the special problems encountered where power lines cross over telephone, telegraph, and railway lines.

Among those who have taken part in the discussion on the paper are some who are associated with the telegraph and telephone interests of this country, and it is with regret that the authors notice that so many of the speakers, when referring to mechanical difficulties, have obviously had in mind the special peculiarities of these particular branches of engineering, rather than the heavier and quite different circumstances of power service, such as, for instance, the swinging and rippling of wires. In the authors' statement that conductors do not swing together, they had in mind lines properly designed with this point in view and not lines put up haphazard or very light lines. The synchronous swinging of wires is a function of their exposed area, weight per foot-length, design of towers, spacing of conductors, method of attachment of same, etc.; and the prevention of this trouble is only a matter of careful design, though one on which a mathematical treatise might be written. The rippling of wires is not a thing which need cause any trouble with cables of the sizes and spacings as used in power work, though of course very common in telephone and telegraph construction. A rule followed by some engineers is that, independent of electrical reasons, as mentioned in paragraph 8 on page 575, the wire spacing should be 1 ft. per 100 ft. of span. This approximation, of course, is only used for power lines and for wires rigidly attached to the supports.

With regard to the question of flexible towers, the authors have been very active in helping the development of this work in the United States, not that they consider this construction to be a panacea for all ills, but because it has been the duty of one of them to keep in the very closest possible touch with, and to lead as far as possible in,

Messrs. Matthews & Wilkinson.

all the latest developments of transmission. Mr. Trotter, to judge from his remarks, did not apparently read the authors' paper very carefully, for they have dealt with the subject of flexible towers very definitely from a practical point of view, since they gave the outcome of very careful mathematical analysis of the subject combined with the special modifications which are necessary to conform with commercial conditions. They, further, maintain their opinion that the amount of deflection of a flexible tower is essentially a practical matter, since it is the first point to be considered, and they further believe their solution to be the shortest and most simple yet given, that has proved accurate for all practical purposes. It has certainly been borne out in instances of actual lines that have been constructed on this basis. The practical side of this question alone is sufficient for a lengthy paper, and accordingly they attempted to sum up in the cost curves the entire result of all the practical investigations. These curves are based on actual results obtained from close co-operation and experience on practically all the lines of this character yet installed in the United States, and their work has made it necessary for them to go very thoroughly not only into details of design, but also into questions of foundations, methods and costs of erection, the strength necessary, both along the line and at right angles to it, etc. With regard to Mr. Trotter's question as to what happens when the line is wrecked, the reply is that this depends entirely upon the mechanical design of the whole system and the number of wires broken by the wreck. If, however, it means that the line has been so badly placed that a big tree can, and does, fall across it in such a way as to break all the wires, actual test has shown that in quite severe conditions only one flexible tower on each side of the break will be lost. Roughly speaking, the question of strength along the line can be answered by the statement that it must be sufficient to stand the stress imposed by erection of the towers and stringing of the particular size of wires to be carried. Mr. W. B. Esson presumes that we put forward flexibility as the pre-eminent feature in the construction of a flexible tower line. The original intention, of course, was to save cost without sacrificing efficiency, which should be the original intention of all sound engineering work. It is not in accordance with modern practice to use great masses of concrete for foundations, as is suggested by Mr. Esson, except under special circumstances, since it is not needed for the majority of cases, and it will be noted on reference to the specification for steel transmission line towers in the Appendix that the definite statement is made that "No concrete foundations are to be used except for swampy ground or angles in the line."

The wood poles referred to in the paper are untreated ; however, not only is creosoting considerably employed in the United States, but also very many other methods, such as "kyanising," "burnetising," "well-house process," "vulcanising," etc., which increase the life in varying degrees ; they mean, however, in every case, a considerable additional expenditure for the poles, which is not allowed for in the cost curves given.

Messrs. Matthews & Wilkinson.

With reference to the question as to the life that may be anticipated for poles used for power transmission work, a matter which was dealt with by a number of speakers, it is necessary to emphasise a point that apparently they have overlooked. It is, of course, that for this work specially selected poles have to be employed, as they have to be both stouter and longer than those used for ordinary telephonic and telegraphic service. This matter of life of wood poles has been carefully gone into by the United States Department of Agriculture, and from the results of their investigations there is nothing to show that the life of transmission line poles will be anything like that suggested by various speakers. Further, Italian engineers have found the life of wooden poles to be even shorter than that which American experience points to. Of course, the ordinary life of a transmission line pole is only two-thirds of the time which would be taken for the pole to seriously deteriorate, since it does not do to run any unnecessary risk with these high-tension lines. These poles are tested from time to time by trial borings. Regarding the kind of wood adopted in the United States, the principal varieties are cedar, chestnut, all the oaks, also juniper, pine, and several other kinds are sometimes employed. On the Pacific Coast, redwood and cedar are largely used ; in the Western States, cedar and pine ; in the Southern States, pine and juniper ; while in the Eastern States, white chestnut and cedar are employed.

So far as the life of steel towers is concerned, it is a matter to a certain extent for assumption, but a good deal of experience has been obtained in America with galvanised towers that have been up for a period of twenty years, and from their present appearance there is every probability of their lasting very much longer, as they show no signs of deterioration, even at the ground line. Painted towers are not so much used, since of course they have to be re-painted every three or four years, and even then there is considerable trouble experienced at the ground line which can only be overcome by a protective base of concrete or by galvanising the lower ends. It is not general or good practice to paint galvanised towers. On referring to the Appendix to this paper it will be noted that the specification for the galvanising of steel towers for transmission lines is very rigid, and it is of interest to remark that the makers in the United States, who have specialised in the construction of these towers, have made very long galvanising tanks so that very large component pieces of these towers may be galvanised at one and the same operation. Mr. B. Welbourn asked whether any system has been employed of automatic protection to the lines in the event of a fault, such as the Merz-Price protective gear. In reply the authors would say that while these systems have been investigated, none of them have been adopted, both on account of the added complication and, further, the fact that these systems have not yet been developed for use in conjunction with lines operating at extremely high pressures. The same speaker refers to the use of "iron" earth wires. The practice in the United States, however, is to use a superior material in the form of ⅜-in. Siemens-Martin double

galvanised, stranded, mild steel cable. As the steel of which this cable is made is of very uniform composition, there is no doubtful question as to life or strength that cannot be taken care of in the preliminary calculations. Further, it is cheaper than copper for the same section. There is no object in using a wire of small diameter, since dependence is placed on the skin effect for conductivity. The suggestion that the earth wire should be placed under the transmission wires is, of course, absurd. While admittedly a contentious matter, as the result of considerable experience, American engineers on the whole are in favour of the employment of earth or ground wires mounted over the conductors, since they have proved to be of so much value. The authors recently recommended this system, with success, to overcome serious troubles with some long lines in the South of France. Messrs. Matthews & Wilkinson.

Mr. Welbourn was very emphatic on the point that aluminium lines do not collect so much sleet as copper lines. The authors regret that they cannot change their views on this question, since their statement is based on a large number of carefully made observations carried out practically all over the sleet districts of the United States. Aluminium transmission line wires are not employed by any engineers who have really had a wide experience in the construction of transmission lines, except under the special condition, when the market prices were such as to make an enormous saving. The whole question may be summed up by the attitude that "Aluminium is a cheap substitute for copper." It is softer, not so strong, and has a greater sectional area for the same conductivity. It can never therefore be as good as copper, and it is certainly not the safest and best practice to adopt. It is unfortunate that one or two speakers have referred to the 110,000-volt transmission system recently put into operation by the Hydro-Electric Power Commission of Ontario, upon which aluminium has been employed throughout, for this line is not a good example of sound engineering design, and troubles have been experienced in its operation. Mr. E. J. Fox suggests that the authors have not mentioned tubular steel poles. They would, however, refer him to the paragraphs on page 567 of the paper headed "Steel Poles," wherein is pointed out the evident objection to this form of support for the larger lines. Mr. Fox's estimate as to the speed of erection is considerably under the mark, since it is the usual practice to erect 5 to 10 rigid towers per day and 8 to 16 flexible towers, in both cases on foundations that have been previously prepared. Mr. E. H. Rayner suggests that the authors have not given any values for the factors as to the wind velocity, etc. This information can be found in most of the standard engineers' pocket-books, and accordingly it is not worth while repeating it here. The points he refers to in connection with the design of insulators are, of course, well known to insulator makers and users, and any standard specification which calls for good "wet process porcelain" would bring forward a product free from this defect. Mr. F. V. T. Lee, in his remarks, touched upon a number of points which, though interesting, have very little to do with the scope covered by the paper. His

Messrs. Matthews & Wilkinson.

suggestion that steel poles should be used is not a good one, as poles have too many disadvantages when employed in connection with the extra-high-tension lines referred to in this paper. With reference to his comments on the design of suspension-type insulators, it may be pointed out that the more recent designs are evidently a very great advance on those of which he has had experience.

Mr. Esson cites two instances of the adoption of extra-high-tension lines of comparatively short length, viz., a 14-mile line operated at 60,000 volts and a 50-mile line operated at 110,000 volts. The consideration which led to a choice of these particular voltages was mainly the provision for future extension on the voltage selected, for which these lines are ultimately required. They will then form an economical arrangement, which, of course, they do not at present. Mr. Esson pointed out that with a star connection the pressure between the conductors and earth is predetermined in such a fashion that it can never exceed 58 per cent. of the pressure between two wires, and deduces from this—as has also been done by others—that the insulation required for a line need only be 58 per cent. of that required for an undergrounded line. Though when the grounding is perfect this is theoretically correct, it is not the case when the neutral is connected to earth through a resistance, as in the instance of a fault to earth on one phase; in this case the two other phases may for a short time be subjected to a voltage to earth nearly equal to the full-line-voltage. So that whether star or Δ connection is adopted, the insulation should be the same in either case. This question of Δ *versus* Y connection is quite complex, and, further, a very big matter that cannot be answered offhand. It should be noted, of course, that the Y connection is quite a different thing if it be grounded or ungrounded, grounded direct or through a resistance, bound with other Y's or with Δ's, etc.

Mr. A. A. Campbell Swinton inquires whether anybody has considered the question in regard to the use of iron or steel conducting wires on extra-high-tension overhead lines. The objection to this is that the inductance is too great for main lines. Iron or steel wire can be used for small power feeders tapping off extra-high-tension lines, but the field is so limited that the authors do not know of any case where it is employed with the exception of a special application which has been adopted in certain towns in conjunction with a series arc-lamp system. Here, of course, the voltage is comparatively low. In the course of his remarks Mr. Swinton assumes that the word "corona" is employed as the American expression for brush discharge. That, however, is not the case. Brush discharge is still used to describe the same phenomena both in the United States and in this country. The word "corona" refers to the crown or ring-like appearance of the glow around the wire, which occurs long before a brush discharge commences. Of course, when the latter occurs, it is very quickly followed by a breakdown of the line.

Dr. M. Kloss refers to the curve (Fig. 13) the authors have given

Messrs. Matthews & Wilkinson

showing the increase of corona losses with an increase of voltage, and he is correct in assuming that it follows more than one law. In fact, it follows one law in its lower range, another at the point of change, and then, after the change, suddenly conforms to a third law. He suggests that the flat portion of the curve, up to about 115,000 volts, is not due to corona effect at all, but rather represents the watt loss of the charging current. This is not the case, for the losses shown in the curve are purely due to the corona, the other losses being separated out. Further on in the course of his remarks he gave a very kind appreciation of the suggestions made by the authors to the effect that a line should be operated at a voltage only slightly below the critical point, and in this connection they may say that this condition has been complied with on one 100,000-volt line, and one 110,000-volt line, and so far these lines seem to behave in accordance with all anticipations. Referring to the question of the limit of pressure, raised by Mr. Cramp, it might be of interest to mention that the line illustrated in Fig. 12 has already been operated at a pressure of about 300,000 volts. Two lines, each of about 400 miles in length, are at present under consideration to operate at 165,000 volts, but the authors are not at liberty to give any further information regarding them at present; whilst a 250-k.w. transformer has recently been constructed for 400,000 volts. Experience shows that all the more serious troubles in transmission-line operation occur between 30,000 and 80,000 volts; above and below those points the troubles are very much less. Mr. Cramp has misunderstood the information given on page 567 of the paper, as the reference there is to steel poles, and not towers. In the latter case, naturally, very much longer spans can be obtained, examples of which are the St. Joquin river span of about 3,000 ft., and the Coquinez Straits span, which is about 4,200 ft., and is the longest crossing in the world.

The authors take the opportunity of expressing their gratification at the length of the discussion, and their appreciation of the valuable suggestions which have been brought forward by the various speakers in the course of the seven meetings which were occupied in the discussion of this paper.

Mr. W. T. Taylor's reply to the discussion on his paper will be found in a subsequent number of the *Journal*.

A vote of thanks to the authors was carried by acclamation.

Proceedings of the Five Hundred and Sixteenth Ordinary General Meeting of the Institution of Electrical Engineers, held on Thursday, February 9, 1911—Mr. W. DUDDELL, F.R.S., Vice-President, in the chair.

The minutes of the Ordinary General Meeting, held on January 26, 1911, were taken as read, and confirmed.

Messrs. W. P. Digby and J. F. Heath were appointed scrutineers of the ballot for the election of new members, and, at the end of the meeting, the following were delared to have been duly elected :—

ELECTIONS.

As Members.

Alex Dow.
Dr. Max Ludwig Kahn.

As Associate Members.

John Graeme Balsillie.
William Francis B. Bartram.
Walter Henry Bray.
James Greaves Hill.
John McCarthy.
Alexander Hill McKay.
Fred Mellor.
Harold Arthur Neale.
Charles Powell.
Walter E. Rogers.
Jacob Carl Russell.
Georges Schauli.
George Hubert Smyth.
Francis Powell Talboys.
Jean Eugene Tarby.
Harold Ernest Trent.
William John White.
Arthur Evelyn Williams.
Joseph Henry Wright.

As Associate.

James H. Webb.

As Students.

Frederick G. Baxter.
Charles Richard G. Cosens.

Donations to the *Library* were announced as having been received since the last meeting from W. Brew, S. Hirzel, A. E. Kennelly, J. W. Meares, The Phœnix Assurance Co., Ltd., John Smith & Sons, Ltd., E. & F. N. Spon, Ltd.; to the *Building Fund* from R. H. Burnham,

R. A. Dawbarn, F. C. Taylor; and to the *Benevolent Fund* from W. R. Rawlings, W. C. P. Tapper, the Executors under the will of the late Mr. Gustav Byng, to whom the thanks of the meeting were duly accorded.

The adjourned discussion on Mr. W. T. Taylor's paper (1) "Modern Long Distance Transmission of Electrical Energy" (see page 510), and Messrs. R. Borlase Matthews and C. T. Wilkinson's paper (2) "Extra High Pressure Transmission Lines," was resumed (see page 562), and the meeting adjourned at 9.45 p.m.

Proceedings of the Five Hundred and Seventeenth Ordinary General Meeting of the Institution of Electrical Engineers, held on February 23, 1911—Mr. S. Z. de Ferranti, President, in the chair.

The minutes of the Ordinary General Meeting, held on February 9, 1911, were taken as read, and confirmed.

The list of candidates for election into the Institution was taken as read, and it was ordered that it should be suspended in the Hall.

Donations to the *Library* were announced as having been received since the last meeting from H. R. Kempe, Prof. J. A. Ewing, W. P. Maycock, Major W. A. J. O'Meara, Messrs. F. C. & W. H. Smith, The Cambridge University Press, Messrs. E. & F. N. Spon, Ltd., Messrs. The Peel Conner Telephone Works, Ltd.; to the *Museum* from Sir David Salomons, Bart.; to the *Building Fund* from A. D. Constable, Dr. C. V. Drysdale, S. Z. de Ferranti, T. L. Fisher, C. Hardy, Col. H. S. Hassard, Prof. A. Hay, J. F. Henderson, A. E. Levin, G. C. Lloyd, E. Mercer, W. M. Mordey, F. H. Nicholson, A. P. Pyne, S. R. Roget, Sir David Salomons, Bart., J. F. C. Snell, A. Stroh; and to the *Benevolent Fund* from G. F. Allom, M. S. Chambers, R. A. Chattock, W. C. Clinton, V. K. Cornish, B. Davies, J. Devonshire, H. C. Donovan, B. M. Drake, Dr. C. V. Drysdale, K. Edgcumbe, Dr. R. T. Glazebrook, F. E. Gripper, Col. H. S. Hassard, C. C. Hawkins, K. Hedges, J. S. Highfield, H. A. Irvine, E. S. Jacob, Dr. G. Kapp, A. E. Levin, E. Manville, W. Mead, L. B. Miller, W. M. Mordey, Major W. A. J. O'Meara, Hon. C. A. Parsons, W. H. Patchell, A. H. Preece, Sir W. H. Preece, W. L. Preece, T. Rich, R. Robertson, S. R. Roget, W. H. Scott, A. Siemens, J. F. C. Snell, A. Stroh, A. J. Stubbs, F. J. Thompson, A. P. Trotter, H. W. L. Ward, to whom the thanks of the meeting were duly accorded.

The adjourned discussion on Mr. W. T. Taylor's paper (1) "Modern Long Distance Transmission of Electrical Energy" (see page 510), and Messrs. R. Borlase Matthews and C. T Wilkinson's paper (2) "Extra High-pressure Transmission Lines" (see page 562), was concluded, and the meeting adjourned at 10.5 p.m.

MERZ-PRICE PROTECTIVE GEAR AND OTHER DISCRIMINATIVE APPARATUS FOR ALTERNATING-CURRENT CIRCUITS.

By K. FAYE-HANSEN and G. HARLOW, Associate Members.

(*Paper received November* 24, *read before the* MANCHESTER LOCAL SECTION *December* 20, 1910, *and before the* BIRMINGHAM LOCAL SECTION *on January* 11, 1911.)

This paper is intended to deal only with devices for protection against excessive currents and not with protective apparatus which deals with over-potential. It must, however, be remembered that excessive voltages are sometimes caused by heavy currents, so that effective protection against over-currents in many cases prevents dangerous voltage rises.

By discriminative protective devices we refer to those which have been suggested or adopted to cut out faulty apparatus only and to leave healthy apparatus in circuit absolutely unaffected by fault external to them.

For the protection of distributing systems there are three main methods of carrying out discrimination, viz.:—

1. Overload time-limit protection.
2. Reverse energy apparatus.
3. Merz-Price protective gear.

Overload Time-limit Protection.—The adoption of overload time-limit protection is limited by the number of points in series at which the system is to be protected and by the use of ring mains on which overload time-limit apparatus cannot be used, since the number of points in series from the generators vary on each side of the ring, depending upon, whether the ring main is open at any point, and at which point it is open. For instance, referring to the ring main, which, as shown diagrammatically in Fig. 1, is fed from two generating stations, A and A_1, it would obviously be impossible to protect such a system by means of overload time limits, since the length of the time limit required for each breaker in sub-stations S, S_1, S_2, etc., depends upon which generating station is feeding the network, and whether the two of them are operating together or not.

There are, of course, many cases where the overload time-limit protection can be applied very effectively, either with the fixed time-limit system or the inverse time-limit system. In many systems a combination of fixed and inverse time limit protection will give every satisfac-

tion, the fixed time-limit relays being installed nearest to the power station, and the inverse time limits at points further away. The advantage of the inverse time limit is, that it will operate quicker the heavier the fault. For protection of points in series, this is a disadvantage, as in case of heavy fault the switches will all operate at the same time, so that no discrimination takes place. With fixed time limits the speed of the operation is independent of the size of fault, so that it is easy to obtain discriminative action, but for the points near the power-station the time taken to operate will have to be made longer than desirable should there be many points in series. A combination of fixed and inverse time limits makes it possible to have more points in series without the time limit nearest the generating station having too long a setting. One objection to all time-limit systems (particularly those with fixed time limits) is that a fault is not immediately cut out, but has time to increase, so that the cables or apparatus may suffer more than if instantaneous protection is adopted. It may also mean

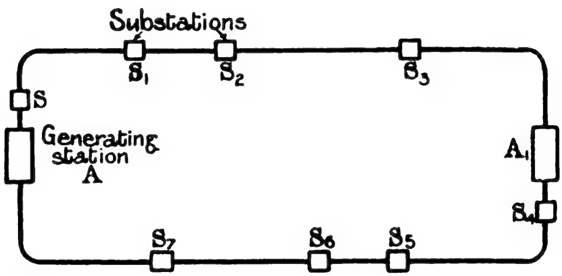


FIG. 1.

that surges are set up when the fault is cut out, causing damage to the insulation of different parts of the system.*

Reverse Energy Apparatus.—Reverse energy protection can only be used where power is flowing in one direction alone when the section protected is healthy, and cannot therefore be used in interconnectors, ring mains, etc., where the power may reverse under normal working conditions, depending upon the distribution of the load and whether the ring main is open at any point or not. There is further the well-known objection to reverse energy relays, that their operation is endangered by the large drop in voltage in case of a heavy fault. This argument against reverse energy relays has probably been over-emphasised in proportion to its importance, as there exist means of reducing the risk to a minimum.

Reverse energy protection is mainly used at the incoming (power receiving) end of parallel feeders, or in connection with alternators,

* For a full discussion of overload time-limit protection, see C. C. Garrard, *Journal of the Institution of Electrical Engineers*, vol. 41, pp. 588–633, 1908; and L. Andrews, ibid., vol. 34, pp. 438–464, 1904.

motors-generators, etc., working in parallel. Reverse energy relays have been described and discussed* so often and fully that it would be superfluous here to re-state their merits or demerits.

Merz-Price Protective Gear.—As is well known, this protective gear is based upon the fact that the currents (or the energy) flowing in and out of apparatus or cables are equal (neglecting losses). In case of fault, however, this condition is changed, and the change is utilised for the operation of the switches. This protective gear is therefore inherently a discriminative system, while all the others can only be made so by skilful adaptation.

The protective gear described has the great advantage that only faulty apparatus is cut out of circuit, and this is accomplished instantaneously. It can be used for nearly all conditions, and its general use is mainly limited by the necessity for pilot wires and the cost which these entail. The gear is shown in its simplest form in Fig. 2, which illustrates the protection of a single-phase transformer, there being two

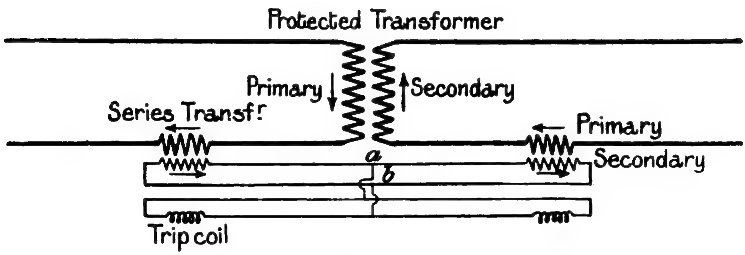


FIG. 2.

series transformers, one in the primary and one in the secondary of the protected transformer. These two series transformers are arranged so that their secondary currents are equal, and flow in the same direction round the local circuit formed by their two windings. The whole E.M.F. of this secondary circuit is consumed in overcoming the internal impedance of the two series transformers, since the resistance of the connecting leads between the secondaries can be made negligible. Hence, if trip coils be connected across the secondary circuit, as shown, no current will flow through them, because no potential exists across the two points *a* and *b*, so long as the currents in the protected transformer flow in a normal direction and have the normal ratio. Should, however, the ratio between primary and secondary currents of the protected transformer be changed, as will happen when a fault occurs in the transformer, the secondary currents of the two series transformers will differ in value or phase, or both, and this vectorial difference will flow through the trip coils and, if large enough, operate them. It is easy to pre-determine the fault current (in percentage

* See L. Andrews and C. C. Garrard, *loc cit.*

of the full-load primary or secondary currents) necessary to operate the trip coils, as the ratio of the series transformers remains constant, providing they are large enough to furnish the necessary volt-amperes for operating the trip coils. It is, of course, possible to design the gear to trip at as large or as small a fault current as desired, but the series transformers will have to be larger the smaller the fault current required for operating, compared with the standard full-load current passing through the circuit. The reason for this is that the series transformers have to give a certain output at the moment of tripping, while the currents they have to carry at normal full load are correspondingly higher if the tripping current is less than the normal full-load current.

Another form of the protective gear, the so-called "Magnetic Balance System," is shown in Fig. 3. The series transformers are designed so that their secondary currents normally are equal, and the windings of the "balancing transformers" are made in such a way that

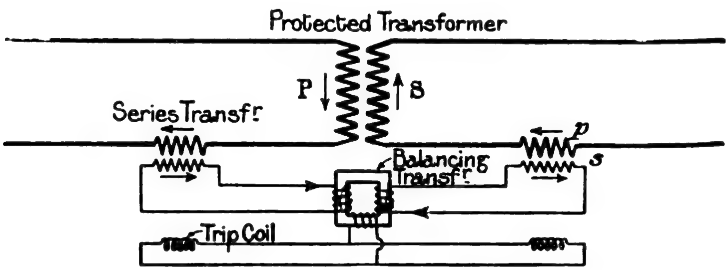


FIG. 3.

the resulting ampere-turns on the core are zero, as long as no fault occurs. Under these circumstances no current will flow through the trip-coil circuit, as no electromotive force is induced in the winding connected to the coils. If a fault occurs, however, the ampere-turns on the two legs of the balancing transformer will be unbalanced, there will therefore be induced an electromotive force in the winding in series with the trip coils, and providing the fault current is large enough, the trip coil will operate. If the series transformers and balanced transformers are large the current through the trip coils will again be proportional to the fault current. This method of protection was adopted in practice before the balanced current system, but has no advantage over it, and requires an extra transformer. In both systems instruments, relays, etc., may be connected in the secondary circuits of the series transformers if desired.

In Figs. 2 and 3 the trip coils are shown connected in parallel, but can equally well be connected in series.

Fig. 4 shows the balanced current system adapted to a single-phase feeder. In this case the resistance of the pilot wires between the

secondaries of the two series transformers is not negligible, so it is necessary to connect the trip coils to points which have the same potential when the feeder is healthy. There is an infinite number of pairs of such equipotential points of which the two points midway between the series transformers form one, and the points *a* and *b* another. It will be noted that for this connection three pilot wires of the total length of the distance between the feeder ends are required for the protection of a single-pole single-phase feeder. It will also be

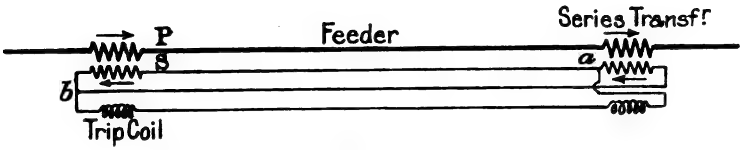


FIG. 4.

noted that in case of a fault the series transformer will have to force the trip current through these pilot wires in addition to the trip coils. In this diagram the two trip coils have been shown connected in series. If connected in parallel one pilot wire more would be required; this is shown in Fig. 2 for transformer protection. In the parallel connection both trip coils are likely to operate together, since if one starts before the other it will take less current, and the backward coil will receive correspondingly more, its tripping

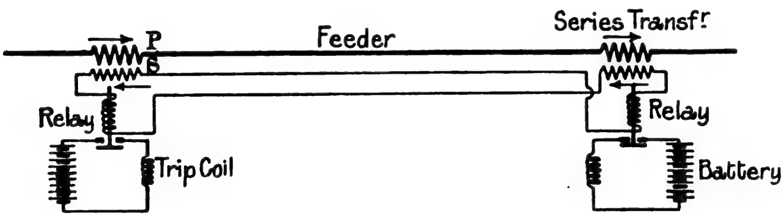


FIG. 5.

action being hastened. In the series connection the current will remain the same in both trip coils, so that the trip coil which starts to operate first will take the highest voltage and therefore have the largest pull. Compared with the saving of a pilot wire for feeder protection this point is of no importance. On account of the extra pilot wires, etc., the balanced current system has, to the authors' knowledge, never been used in practice in conjunction with feeder protection. For this service a balanced voltage system, as shown in Fig. 5, has been invariably used. This diagram shows the arrangement for a single-phase single-pole system, and in this case the secondaries of the series transformers are connected in such a manner

that they oppose each other when current is flowing through a healthy feeder. These series transformers have to be adjusted so that the secondary voltages induced in both are identical in magnitude and phase at all primary currents. With such transformers no current will flow through the pilot wires or relays so long as the feeder is healthy. If, however, a fault occurs in the feeder between the two series transformers, the current flowing in the primary of these will be different in amount or phase, or both, and hence in the secondaries of the series transformers the electromotive forces will also be different. This difference in E.M.F. will force a current through the pilot wires, relays, and secondaries of the series transformers, which current, when large enough, will operate the relays and close the battery circuit through the trip coil. In this system it is not so easy to predetermine the fault current at which the relay will operate, as the fault current in one series transformer must induce an electromotive force large enough to overcome the impedance of the comparatively long pilot wires, the relays, and also of the other series transformer, so that the magnetising current of the series transformers will be a large part of the primary fault current; if therefore the relays are not designed for a comparatively low volt-ampere operating capacity, the series transformers must be very large. This is the reason why in Fig. 5 a relay is shown in conjunction with the protective gear, while in the other cases it is proposed to operate the trip coil direct from the secondary of the series transformer without the use of any relay. It is possible, of course, in case of the balanced voltage system, to use trip coils direct in the circuit as shown in Fig. 6, and for very short feeders this arrangement can be adopted without too large series transformers being required. The balanced voltage system is similar to the balanced current system in that the series transformers have to be made larger if it is desired that the gear shall operate at a fault current small compared with the normal full-load current.

Fig. 7 shows the balanced current method adapted to the protection of a star-wound 3-phase alternator. It will be noticed that three of the series transformers are located at the star-point of the machine, and hence it is necessary either to mount the series transformers adjacent to the alternator or to bring the three leads from the star-point of the generator to the switchboard and make the connection in the cubicles.

In Fig. 8 is shown the protection of a delta-wound 3-phase alternator; this requires the mounting of all six series transformers adjacent to the machine, or the carrying of six leads from the generator. When used for generators the Merz-Price gear can only protect against fault to earth or between phases, but does not take care of breakdown between different parts of one phase or loss of field or loss of power, so that we do not recommend its use for generators.

The protection of a 3-phase transformer connected star to delta is shown in Fig. 9, and here it is necessary to connect the series transformers star to delta in the reverse manner to that in which the main

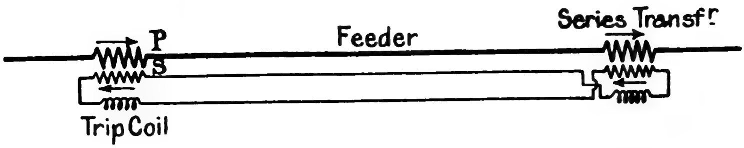


FIG. 6.

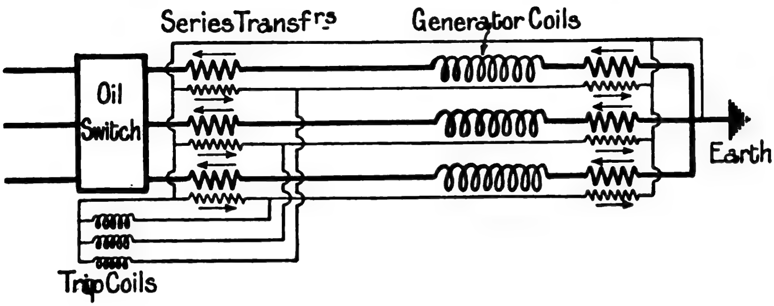


FIG. 7.—γ-wound Generator.

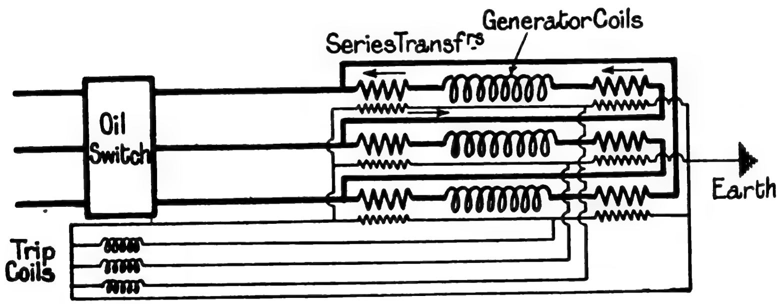


FIG 8.—Δ-wound Generator.

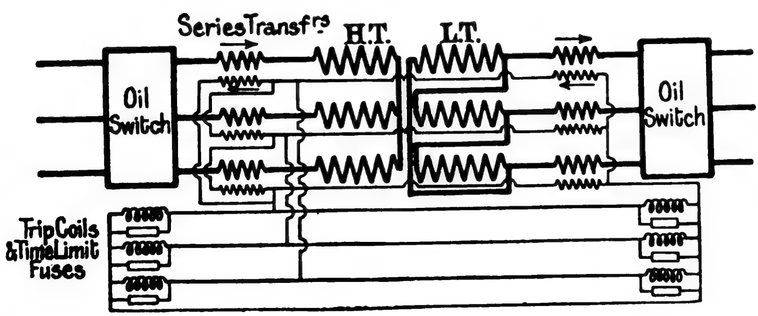


FIG. 9.—γ–Δ Transformer.

transformers are connected, that is to say, where the main transformer is connected in delta the series transformers are connected in star and *vice versâ*. Another method of connection would be to have the series transformers inside the delta of the main transformer bringing out six leads, the secondaries of the series transformers having then the same connections on both sides. The fuses shown are necessary to prevent the rush of magnetising current during switching operations (which, of course, flows in the primary side of the transformer only) from passing through the trip coils and tripping the switch. Experience has shown that this is necessary for both polyphase and single-phase transformers, though the fuse is not shown in Figs. 2 and 3. Normally, these fuses carry only a current proportional to the magnetising current of the transformer. In case of transformers having tappings it is necessary to bring out corresponding tappings on the series transformers in order that the ratio of the series trans-

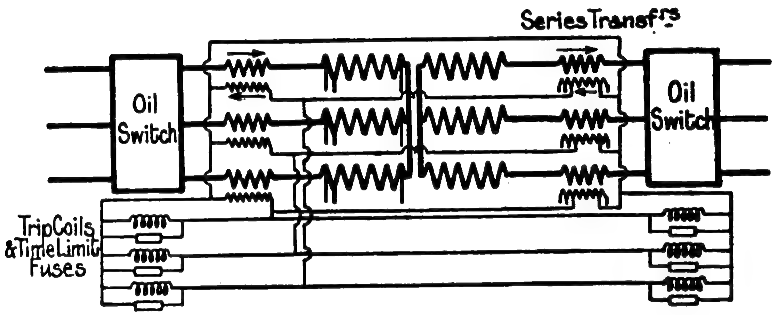


FIG. 10.—γ–γ Transformer with Tappings on High-tension Side.

formers may be changed when the voltage ratios of the main transformers are altered, otherwise the gear will operate at heavy overloads.

Fig. 10 shows an arrangement for a 3-phase transformer connected star to star with tappings on the high-tension side of the protected transformer and on the secondary side of the low-tension series transformers.

In the above cases the balanced current and balanced magnetic systems have been shown applied to the protection of transformers and generators and the balanced voltage system with relays applied to the protection of feeders.

Any of the systems can be used for the protection of generators, transformers, or feeders, and their application depends upon characteristics which will now be discussed generally.

Break in Pilot Wire Circuit.—A breakage in the pilot wire circuit prevents the operation of the balanced voltage system in case of fault, and is difficult to locate without frequent testing of the pilot wires. Such a breakage with the balanced current system or balanced

magnetic system results in the immediate isolation of the section in which the fault occurs.

The above results are advantageous or disadvantageous depending entirely on local conditions. As the protective gear is generally used in connection with at least a duplicate supply, it is probably advantageous to have an unprotected section immediately disconnected, since one source of supply is still available and all possibility of false security is removed.

Break in Trip Coil or Trip Coil Circuit.—Such a break renders all systems inoperative.

Balancing of Transformers.—This must be most carefully carried out on the balanced voltage system, whilst in the balanced current system there is no necessity for such accurate balancing, as the ratio of the series transformers decides this point, provided the transformers are chosen of a size suitable for the work.

Use of System for other Purposes than Protection.—The balanced voltage system can be used for protection only, whereas the balanced current or magnetic systems may be used in many cases for measuring purposes in connection with instruments.

Losses due to various Systems.—These are in most cases negligible, and take the form of copper losses in the pilot wires for the balanced current or magnetic system, and iron losses in the series transformers for the balanced voltage system.

Power required to Operate.—This point is fully discussed later, but taking the same size of relays or trip coils, the balanced current and magnetic systems require less power than the balanced voltage system ; this is due to the fact that the operating series transformers on the latter system have to overcome the impedance of the opposing series transformers, in addition to the relays or trip coils, whereas in the former system the impedance of the relay or trip coil only has to be overcome.

The authors believe the reasons stated prove that the balanced current system, wherever applicable, has an advantage compared with the balanced voltage system, if it is possible to adopt it without an increase in cost. This can be done without difficulty in the protection of stationary apparatus where the length of pilot wire is small, so that the balanced current or magnetic systems are usually adopted for this service.

In the diagrams for the protection of generators and transformers, the trip coil is shown as being directly operated by the fault current without the use of relays, while in the case of the feeder protection a relay which closes an auxiliary tripping circuit is shown. This auxiliary tripping circuit can be operated either from a direct-current circuit or from an alternating-current circuit, but it must be remembered that in case of a short, the voltage on the feeder will be very considerably reduced, so that in no case is it advisable to use a voltage transformer connected across the main alternating-current circuit for tripping purposes.

It is evident that there is an advantage in having the tripping gear directly operated from the fault current without any relay or auxiliary tripping circuit, for by this means the operation will be more rapid, and two links which might fail are avoided—*i.e.*, the relay and battery. In the case of protection of generators, transformers, etc., the direct operation of the trip coil from the fault current can be obtained without excessively large series transformers, and without causing excessively high voltage in the tripping circuit. The method of direct tripping should therefore be adopted in all cases for such protection. In case of the balanced voltage system, as stated previously, for the protection of feeders, however, the series transformers would have to be very large if the trip coils of the switches were directly operated by the current flowing in the pilot wires, and in case of long feeders the voltage required in the pilot circuit for operation of the trip coils would also be very high, as it is not possible to construct trip coils which will operate at such low volt-amperes as relays. Thus the standard method adopted hitherto has been to have relays in the pilot wires for closing the auxiliary tripping circuit. This auxiliary tripping circuit is usually energised by means of primary batteries or accumulators in the sub-station, and it is very essential that the batteries be given a great deal of attention, as otherwise they might fail to give the required voltage for tripping in case of fault.

Later, a method is described which renders possible the protection of feeders on the Merz-Price system without the use of relays or batteries, and without the volt-amperes required becoming too high. Before going into these connections, however, it is proposed to deal more fully with the points, which have to be specially considered, when designing the gear for the protection of distributing system, referring specially to the balanced voltage method. The special points to be kept in mind in deciding on the suitability of this protective apparatus to deal effectually with all kinds of faults, and yet to remain inoperative under all conditions of overload or surges, are :—

1. The fault current at which the gear is to operate must be well within that expected in case of breakdown when the minimum plant is running in the generating station. This means that the voltage induced in the secondary of the series transformer due to a fault, when the minimum plant is in operation, must be sufficient to force the current required for operation through the pilot wires, opposing transformers and relays (or trip coils).
2. The maximum short-circuit current to be expected through a healthy feeder when the maximum available plant on the system is in operation, should not be large enough to raise the voltage between the pilot wires to a value endangering the safety of the pilot-wire insulation, or to cause a capacity current in the pilot-wire circuit sufficient to operate the relays. Considerable margin must be allowed for any extra-

ordinary high-frequency phenomena which may be expected on the system.

2. The series transformer secondary voltages have to be balanced with extreme accuracy against each other, so that even under the conditions mentioned under point (2) they will not be able to force enough current through the pilot-wire circuit to trip the relays.

Considering point (1) in connection with a 3-phase system protected as shown in Fig. 13, it should be noted that a different size of fault current is required for tripping, depending upon whether the feeder is fed from both points A and B ("both ended"), or from one side only, say from A ("dead ended"). The former case corresponds to a ring main entirely closed, as for instance, in Fig. 1, when the switches in all the sub-stations, S, S_1, S_2, etc., are closed, and the latter to the case of a single feeder into which the upper half of the ring main in Fig. 1 is converted should, for instance, the switch in S_2 be opened. The difference in the two values depends to a large extent on the impedance of the series transformer. Further, a different fault current is required to operate, depending on whether the fault occurs between two phases or from one phase to earth.

Generally the fault current required to trip is greatest in the case of a fault to earth feeding "dead ended," as then the fault current only produces voltage on the secondary of one series transformer, and this voltage has to force the operating current through the relays, pilot wires, and opposing transformers. The total impedance it has to overcome corresponds to 3 relays, 2 series transformers, and a resistance 1½ times that of each pilot wire. In the pilot wire corresponding to the faulty phase the full operating current will flow, and in the other two pilot wires half this value.

For a fault between phases feeding "dead-ended" the fault current induces voltage in the secondary of two series transformers and the impedance to be overcome consists of 4 relays, 2 transformers, and 2 pilot wires. Though the impedance is somewhat increased the load is now divided between two series transformers, so that a smaller fault current is required for operation.

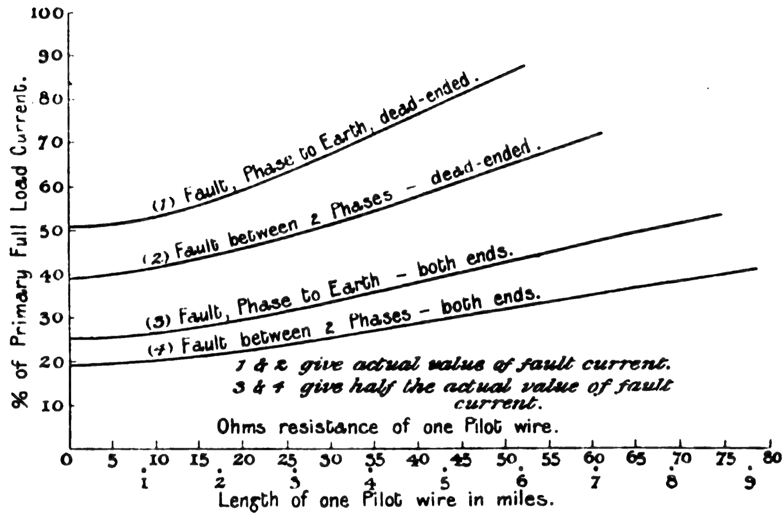
For a fault to earth feeding "both ended," assuming the fault current to flow in equally from sides A and B, then two series transformers again divide the load and the impedance to be overcome corresponds to 3 relays, 1 series transformer, and a resistance 1½ times that of each pilot wire.

It will be seen that the resistance to the operating current is somewhat smaller than in case of a fault to earth feeding "dead ended," and the load is divided between two series transformers, each, however, only being energised by half the total fault current. If the fault current does not divide equally from both sides, then the conditions lie between those described above and those for the case of a fault to earth "dead ended."

For a fault between phases feeding "both ended," 4 series transformers produce voltage and the impedance of the pilot circuit consists of 4 relays and 2 pilot wires.

The ratio between the values of fault current required for operation under the four conditions given above depend entirely upon the relative impedance of the transformer and relays compared with the resistance of the pilot wires. Some typical relative values are given in Curve 1, which shows test results, and also in Table A.

In badly designed systems it may easily happen that the gear will operate when fed from both ends, but will not operate "dead ended."



CURVE 1.

In connection with this it should be noted that the fault to earth is often limited by a resistance in the neutral of the generator or generators.

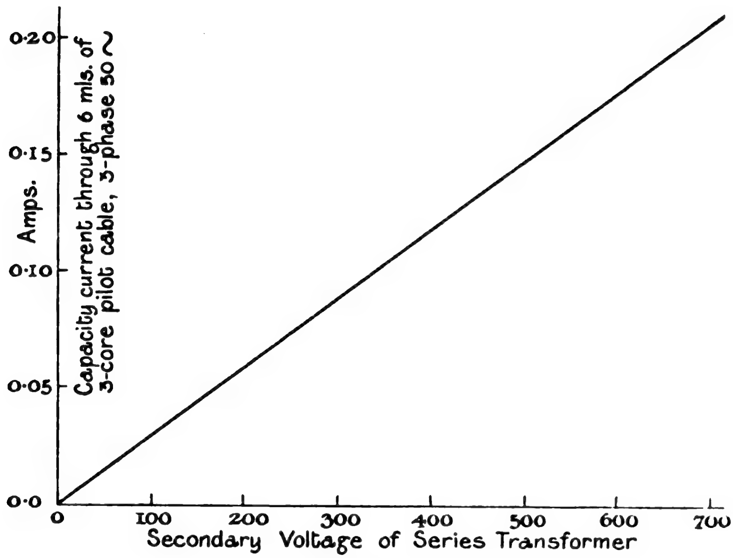
Passing now to point 2, the voltage between pilot wires, in the opinion of the authors, should not, under the heaviest conditions of short circuit, exceed 700 to 800 volts. Of course, it is possible to adopt high-tension pilot wires, but in doing so a further element of risk is imparted to the circuit in the increased probability of the pilot wires breaking down, and the further danger of handling the pilot wire circuit whilst load is on the feeders. The capacity current to be expected in the typical 3-core pilot wire cable, commonly used in connection with feeder protection, is given in Curve 2, for lengths of pilot wires up to 10 miles at a periodicity of 50. The general characteristics of the pilot cable are as follows :—

Fault, both ended to Earth.				Fault, both ended between Phases.			
D.C. Trip.	A.C. Trip.	A.C. Trip.	A.C. Trip.	D.C. Trip.	A.C. Trip.	A.C. Trip.	A.C. Trip.
With Relay.	With Relay.	Without Relay.	Without Relay.	With Relay.	With Relay.	Without Relay.	Without Relay.
Balanced Voltage.	Balanced Voltage.	Balanced Voltage.	Balanced Current.	Balanced Voltage.	Balanced Voltage.	Balanced Voltage.	Balanced Current.
Pilot Wires, 3.	Pilot Wires, 3.	Pilot Wires, 3.	Pilot Wires, 2.	Pilot Wires, 3.	Pilot Wires, 3.	Pilot Wires, 3.	Pilot Wires, 2.
1	2	3	4	1	2	3	4
6·6	61	279	100	2·38	69	96	100
2·6	49	127	95	1·38	54	66	95
200	64	—	—	130	42	—	—
200	200	182	200	130	192	122	200
100	100	91	100	65	96	61	100
13	44	84·5	200	6·9	44	44	200

the same as the four columns filled in under the first "Fault" heading.

(*a*) Size of each core 7/21½ S.W.G. Low-tension 3-core cable, paper insulated and plain lead covered.
(*b*) Capacity of any one core to the other two connected to earth, 0·27 microfarad per mile, and of the three cores bunched together to the lead approximately 0·51 microfarad per mile.
(*c*) Self-induction of one core, 0·53 millihenry per mile.
(*d*) Resistance per mile of each conductor, 8·7 ohms at 20° C.
(*e*) Thickness of dielectric between conductors and between conductors and lead, 0·09 in.
(*f*) Insulation test guaranteed by the makers, 2,500 volts.

From Curve No. 2 it will be seen that in a feeder 6 miles long the maximum capacity current to be expected in the pilot circuit on a



CURVE 2.

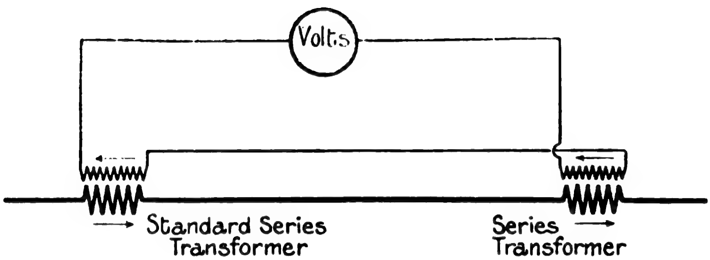
50-period circuit would be 0·2 ampere with 700 volts between the pilot wires, half of this being supplied from the series transformers at each end.

The authors consider that the current at which the relays operate should not be less than about four times the maximum capacity current, thus the minimum current at which the relays can be set to trip for a 6-mile feeder would be 0·4 ampere, providing the design is for 700 volts maximum voltage. If the maximum voltage obtainable is less or the feeder shorter the relays can be set correspondingly lower.

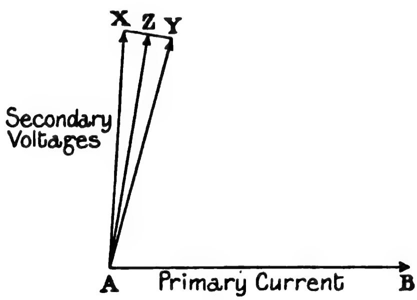
The fairly large factor of safety of 4 has been chosen to allow for any possible high-frequency phenomena and the slight unavoidable lack

of balance between the series transformers. It may be that systems are working satisfactorily with lower factors of safety, as with this figure no difficulty has been experienced.

Regarding point 3, this is mainly a question of accurate testing and adjustment of the magnetic circuit of the series transformers. It is not sufficient to measure the secondary voltage of a series transformer at a given primary current and then assume all series transformers tested in this way will balance with one another. Each transformer must be



(*a*) *Balancing of Series Transformers.*



(*b*) *Vector Diagram for Balanced Transformers.*

FIG. 11.

tested against a standard back to back, that is to say, the method of testing shown in Fig. 11 (*a*) should be used; here it will be seen that the voltage measured is the actual vectorial difference in voltage between the two secondary windings, with the same currents flowing through the primaries. Even with this method there must be slight differences in voltage, as it is not possible to tell whether the transformer under test has a smaller phase angle than the standard or a greater one, and hence some allowance must be made for a slight difference in balance, though this should be reduced to a minimum. It is worthy of note that even if two transformers should have exactly the same secondary voltage

with the same primary currents, still the phase difference of the secondary voltage may be sufficient to cause tripping at heavy overloads should these two transformers be connected back to back. The vector diagram for such differences is shown in Fig. 11 (*b*), where the line A B represents the phase of the current and the line A Z the secondary voltage produced by this current in the standard transformer. The transformers tested against this standard may have such secondary

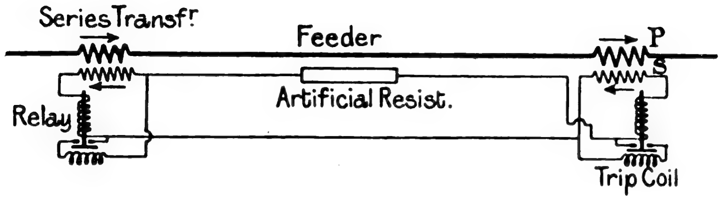


FIG. 12.

voltages as A X and A Y; each of these voltages agree numerically with A Z, but the vectorial difference in voltage between the points X and Y may be quite appreciable, and can only be reduced to an allowable value by careful manufacture and adjustment.

The above remarks have been made with special reference to the arrangement shown in Fig. 13, where three pilot wires and three relays at

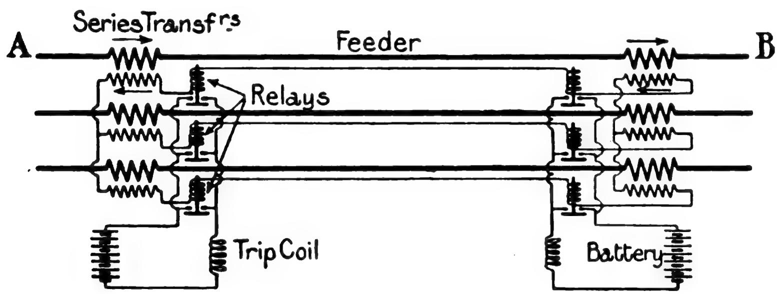


FIG. 13.

each end are used, but they can be applied generally to any balanced voltage arrangement, such as, for instance, the one shown in Fig. 19. Here only two pilot wires are used and one relay at each end, thus effecting considerable economy. If with these connections a fault should occur between phases 1 and 3, then the secondary voltages of transformers in these phases oppose one another, and if they were equal no current would flow through the trip circuit. To overcome this it is necessary to make one of the series transformers at each end with a higher or lower secondary voltage than that of the remainder of the series

transformers at each end; or the arrangement shown using two series transformers in one phase may be used. By this means the arrangement can be made to operate quite satisfactorily; but if we consider the case of a fault to earth on one phase (2 or 3) it will be seen that the value of the primary tripping current must be higher than for the arrangement in Fig. 13 (if the same gear, transformer and relays are used), as the impedance to be overcome consists of 2 relays, 7 series transformers, and 2 pilot wires. By suitable design, however, the system can be made to operate at the same maximum value of fault current as the 3-pilot wire arrangement, though, of course, larger series transformers and higher operating voltages are required. With this connection it is of interest to note that the fault current required for tripping varies, depending upon which phase to earth the fault occurs, or between which phases the fault takes place. However, when the maximum fault current required to trip is within the advisable limit, the variation is not of any importance.

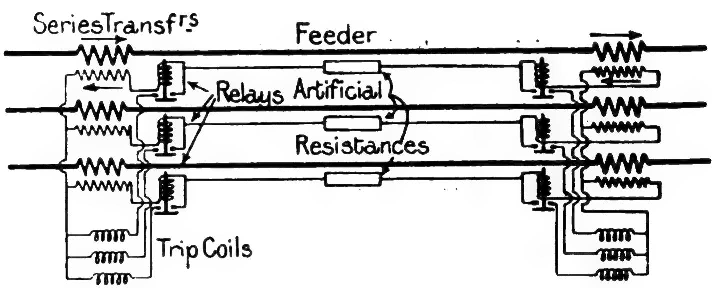


FIG. 14.

Alternating-current Tripping.—The reliability of the balanced voltage system can be increased and the maintenance reduced if in place of direct-current tripping alternating-current tripping be adopted where the tripping is directly dependent on the current flowing under fault conditions. This can be carried out by using special series transformers in each phase for tripping, the relays closing the circuit of these transformers through the trip coils, or preferably as shown in Fig. 12 for a single-phase system, and in Fig. 14 for a 3-phase system. The trip coils are shown shunted across the series transformer secondaries through the relays. A special point to be considered with this connection is that the series transformers, in case of a fault fed from both ends, assist each other to force current in the same direction through the pilot wires, and the voltage across the series transformers—that is, across the trip coils—will depend upon the resistance of the pilot wires. If this is too low, very high fault currents are required for tripping, so that for short feeders an artificial resistance is required, as shown in the diagrams. Against the use of alternating-current trip it has been urged that the relays require to be more robust, due to the

greater volt-amperes required by the alternating-current trip coil; but this is not really important, particularly as the relays have only to close the circuit and not to break any current.

Balanced Current Protection for Feeders.—A further improvement and reduction in maintenance for the Merz-Price protection is obtained by an arrangement which does away with both relays and batteries, and which approaches the simple conditions existing when the gear is applied to transformers. This method is shown diagrammatically in Figs. 22 to 24 for single- and 3-phase cases. Referring to the single-phase case of Fig. 22, it will be seen that the principle is that of the balanced current system whereby equipotential points (under healthy conditions) are obtained in each station by means of tappings from the transformers, secondaries and additional resistances. In the diagram the centre point of each transformer is shown connected to the end of a small resistance, which resistance is equal or approximately equal to the resistance of one of the pilot wires. Under normal conditions of operation, the middle point of the secondary of the series transformers is at the same potential as the end of the resistance, and consequently the trip coil may be connected across these two points without any danger of tripping under all conditions of load. Immediately a fault occurs in the section of the feeder protected by the two series transformers, the middle point of the series transformer and the end of the resistance are no longer equipotential points, and current flows through the trip coil thus tripping the switch. It should be noted that it is not necessary to connect the end point of the resistance to the middle point of the series transformer, but that several points of equipotential occur in series transformer and resistance, and the trip coil may be connected across any of these points; for instance, one-third of the resistance may be connected to one-third of the secondary winding of the series transformer, or three-fourths of the resistance and the secondary winding of the series transformer may be connected.

This method of tripping (for which patent rights have been sought) has, in the opinion of the authors, advantages over those previously proposed, which may be recapitulated as follows:—

1. No relays are necessary, these being replaced by small resistances. The fact that no relays are required apart from the question of reliability and maintenance is advantageous, in that, when this protection is used in fiery mines, there is no danger from the spark caused by the operation of the relay.
2. The direct-current tripping requiring batteries is entirely abolished.
3. There is no necessity for the accurate balance of the secondary voltages of the series transformers, and hence series transformers throughout the system can easily be interchanged, and there is no possibility of the balance being disturbed due to mechanical injury or bad handling of the series transformer. Further, there is no danger of the transformers

supplied for extensions, say, ten years after the original installation, being out of balance.

4. A break in the pilot wires immediately results in the feeder being cut off, thus doing away with any possibility of false security.

Fig. 23 shows one method of adopting this to a 3-phase circuit using three pilot wires, but the authors have not used this connection as standard, since the arrangement of Fig. 24 gives equally good results, using only two pilot wires and one trip coil at each end. For the connection with two pilot wires it is (as previously described in the balance voltage system with two pilot wires) necessary to make the transformer in one of the phases different in ratio and output to the others, or to use two series transformers in one phase.

Detailed Comparison of the various Systems.—For a comparison of the various connections described, it is necessary to make common assumptions with regard to—

1. The fault current required to trip under the least favourable conditions in percentage to the full-load current of the feeder.
2. The ratio between the secondary voltage of the series transformer when full-load current is flowing through the feeder and the voltage obtained when the maximum short-circuit current flows through a healthy section.
3. The length of feeder and size of pilot wire.
4. The safety against tripping due to capacity currents in the pilot wire.
5. Volt-ampere capacity of the relays and trip coils.

The comparison should consist of :—

1. The maximum voltage between the pilot wires under the heaviest fault conditions and when normal load is on the feeder.
2. The size, that is, the volt-ampere capacity of the series transformer. This is of importance, not only from a point of view of cost, but particularly with regard to accommodation in existing sub-stations.
3. General amount of apparatus required, number of transformers, pilot wires, relays, etc.

In the comparison given in Table A the authors have assumed that the gear is required to operate at a fault current equal to the normal full-load current of the feeder taken as 200 amperes; also that the maximum current flowing under short circuit will be in the neighbourhood of 6,000 amperes or 30 times the full-load current in the feeder. This corresponds to an actual system of 6,600 volts, 3-phase, 50 periods, leaving a total capacity of plant 10,000 k.w. and smallest generator

plant running of 2,000 k.w. with a resistance in the neutral not allowing much more than the full-load feeder current (200 amperes) to flow through a fault to earth.

The authors have further assumed that the saturation in the iron of the series transformers is chosen so that at the maximum fault current mentioned (6,000 amperes) the secondary voltage will be approximately five times larger than the voltage when normal full-load current is flowing through the feeder.

The pilot wires adopted are of the kind described earlier, having 0·005 sq. in. section and a length of feeder of 6 miles has been assumed; this length may be somewhat on the high side for most systems, but the gear made suitable for 6 miles will certainly operate satisfactorily for shorter feeders.

The factor of safety against tripping due to capacity current in the pilot wires has been taken as 4; the volt-amperes to open the relays 0·9 volt-ampere, and the trip coils 30 volt-amperes to commence operation, while the volt-amperes of these at the operating current with the plunger up has been taken as 80 volt-amperes. The figures for the relays and trip coils may perhaps be reduced somewhat, whereby the maximum volts between pilot wires and the output of the series transformers could be reduced, but this can only be done to any appreciable extent by making the relays extremely delicate and increasing the danger that the trip coil would not furnish a sufficiently strong blow to trip the switches should these become stiff in operation.

Referring to columns 1 in Table A for "direct-current trip with relays and 3 pilot wires" (Fig. 13), it will be seen that extremely small transformers are required for tripping. Under normal full-load conditions the input to the series transformer is only 41 volt-amperes on the primary, while the secondary output is negligible. When it is realised that a series transformer having the dimensions of Fig. 30 is large enough for an input of 250 volt-amperes at normal full-load current, it will be obvious that a series transformer of 40 volt-amperes can be made very small indeed. The maximum voltage between pilot wires with 6,000 amperes flowing through the primary is only 395 volts, the maximum pressure for tripping 33 volts, and the current in the pilot wires to trip the relay 0·2 ampere. The fault current from the system required to trip is highest for the cases of "fault to earth dead ended" and "fault to earth both ended" being the same for both cases. In the latter case, however, the current through each series transformer is only half the total fault current, and the voltage required for tripping is 13 against 33. For a "fault between phases dead ended" and "fault between phases both ended" the fault current is also the same, 130 amperes, and is approximately 65 per cent. of that for the other two cases. Comparing the figures with those for alternating-current trip with relays balanced voltage 3 pilot wires (Fig. 14) given in columns 2, it will be seen that the output of the series transformer is considerably increased, but the size required is still of the same order

as that of the transformer in Fig. 30—that is to say, a normal-sized series transformer. The output is, of course, increased as the series transformers have to furnish sufficient power to operate the trip coils. The maximum possible voltage between pilot wires rises to 780, the tripping volts to 66, and the relay current to 0·4. The 780 volts would only occur with 6,000 amperes short-circuit current flowing through a

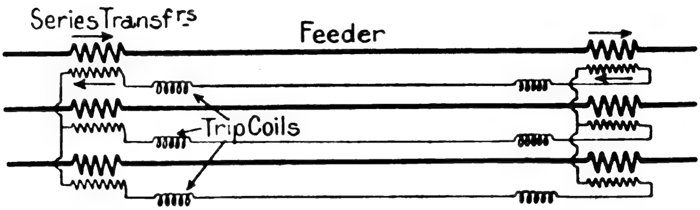


FIG. 15.

healthy section. The maximum fault current required to trip is in the "fault to earth both ended" case, but the value is not greatly in excess of that required for a "fault between phases feeding both ended." The tripping currents required for the "both ended" faults are much higher than for the "dead ended" faults, due to the fact that for the latter cases the trip coil at one end only is operated, while in the former, the

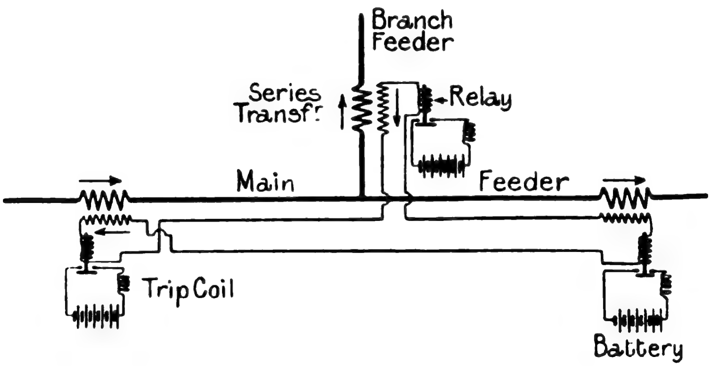


FIG. 16.

trip coils at both ends are operated; and further, in the former case more current flows round the pilot wires without passing through the trip coils. To obtain the above results the pilot wires must be 6 miles in length, or their resistance increased by artificial resistances to a value equal to that of 6 miles of pilot wire, otherwise, as pointed out on page 686, the current in the pilot wires will flow round the circuit instead of going through the trip coils. Further, it should be noticed

that the relays will close at considerably lower values of fault current than the trip coils. Thus the relays may be closed some little time before the trip coils operate, but the figures given for fault currents refer to those required for operation of the trip coils. From the above figures it is evident this method of alternating-current tripping can be adopted effectively.

Columns 3 refer to "alternating-current tripping without relays, balanced voltage 3 pilot wires" (Fig. 15), and the results indicate that this connection cannot be used except for short feeders. For the 6-mile feeder under consideration, the maximum voltage to be expected is 2,940 volts, and the input of series transformers at normal

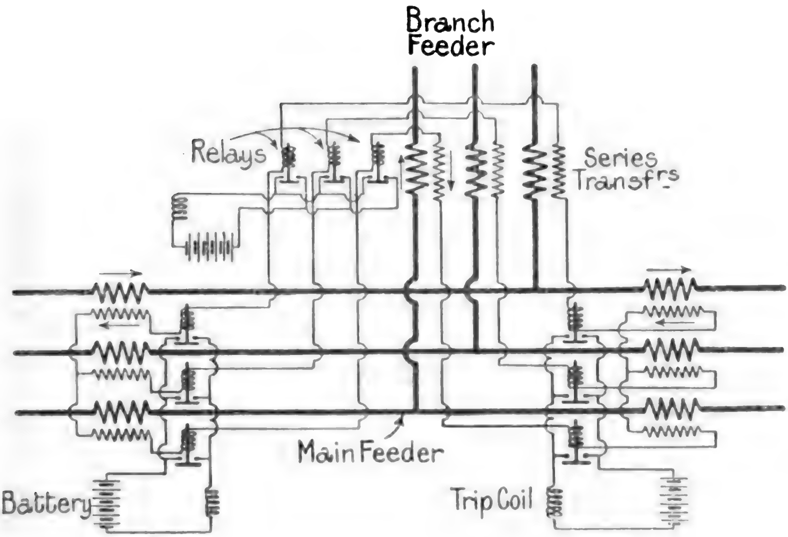


FIG. 17.

full-load current is 2,150 volt-amperes. The voltage of 2,940 is too high, and would necessitate high-tension pilot wires, whilst a series transformer of the size stated would be rather difficult to accommodate in cubicles.

On 25-period circuits the conditions are more favourable since the tripping volts required are very much lower, due to the volt-amperes of the trip coils being lower and the capacity currents in the pilot wires being halved.

Passing to "alternating-current trip balanced current without relays 2 pilot wires," columns 4, which refer to the connection of Fig. 24, the normal input of the series transformer is 125 volt-amperes, which can be obtained easily from a transformer having the dimensions of Fig. 30, though in this case the primary and secondary windings have to be for the same volt-ampere capacity.

The maximum possible volts are 625, and the tripping volts 200. The safety with regard to capacity currents is particularly great with this method of tripping, owing to the large difference between the operating current and the capacity current, and to the fact that this small capacity current does not flow through the trip coils.

Recapitulating the above comparison, it may be stated that the methods of tripping for which figures are given in columns 1, 2, and 4, may all be used satisfactorily, provided the necessary attention is paid to the design of the apparatus and the characteristics of the system to which they are applied carefully studied. The advantages and disadvantages of the various methods have been given earlier in the paper.

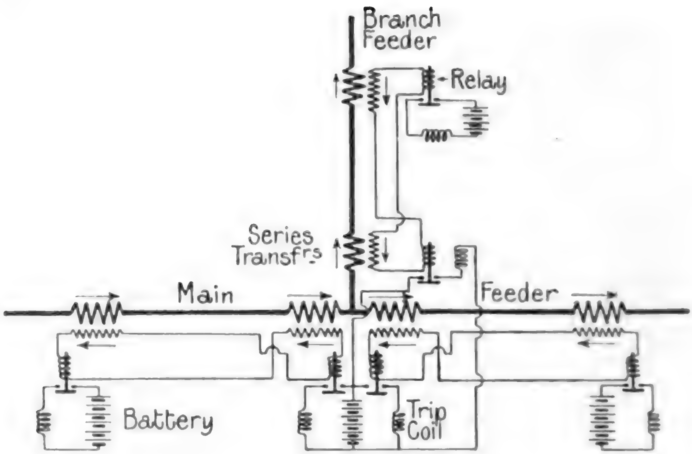


FIG. 18.

With regard to the connection of column 3, it is extremely unlikely that this can be applied successfully for the universal protection of any system, though it might be applied to certain sections of a system. This, however, would not be a wise procedure since the method of protection throughout any system should be capable of application over the whole of the system, in order to prevent complications and to decrease the number of spares carried in stock. Further, it should be remembered when balanced voltage systems are used that ten or even twenty years from the time of the original installation, it must be possible to supply transformers balancing exactly with those installed originally, and the difficulty of obtaining these is increased if various methods of tripping are adopted on one distribution system.

It is interesting to take the series transformers of column 1 and apply them to the 2-pilot wire connection shown in Fig. 19. This is done by using two transformers in one phase. The maximum possible volts between phases become 595 in place of 395, and the safety is reduced

from 4 to 2·3, according to the figures furnished by the makers for the capacity of 3-core and 2-core pilot wires. Further, the tripping current is in the worst case increased from 200 to 375 amperes, *i.e.*, an increase of 87 per cent. Consequently, such applications should be made with extreme care, and if gear is designed

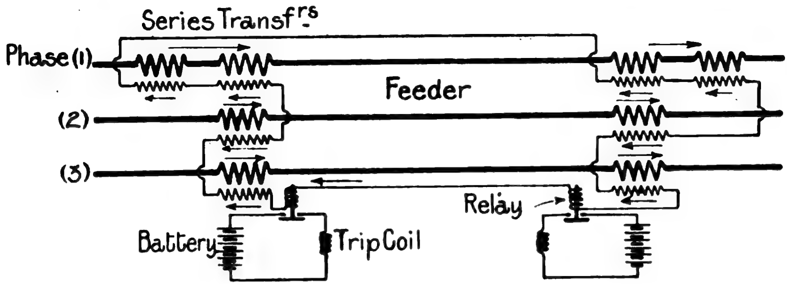


FIG. 19.

to work with 3 pilot wires and has a low factor of safety under those conditions, it is obvious that using the same gear with 2 pilot wires the danger of tripping on overload is greatly accentuated.

Branch Feeders.—When a feeder is branched from one of the sections equipped with the protective gear there are two ways of

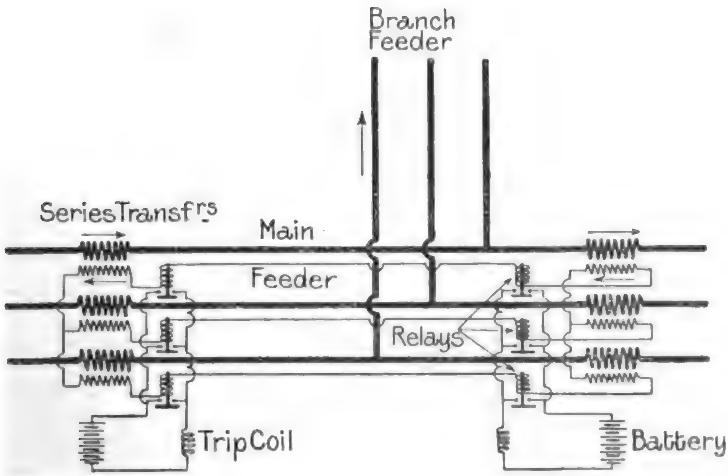


FIG. 20.

dealing with it; either the current flowing through the tapping can be treated as fault current and the relays on the section set so that they will not trip with the maximum amount of load current flowing through the branch, as shown in Fig. 20, or the three points may be

connected up in series, as in Fig. 17, and the voltage of the three points balanced instead of two in the ordinary case. Of course, if the tapping is very large and the service an important one, it will be necessary entirely to protect the points in a similar manner to a sub-station, as shown in Fig. 18, for a single-phase case. Taking first the case of the unprotected joint, it will be seen that such an arrangement could only be adapted successfully for branches taking a small amount of power; for instance, in Table A it will be noticed that when the feeder is fed from one end the amount of full-load current required to trip is 127 amperes, and hence immediately the current through the branch feeder exceeds this amount (for instance, due to a fault at any

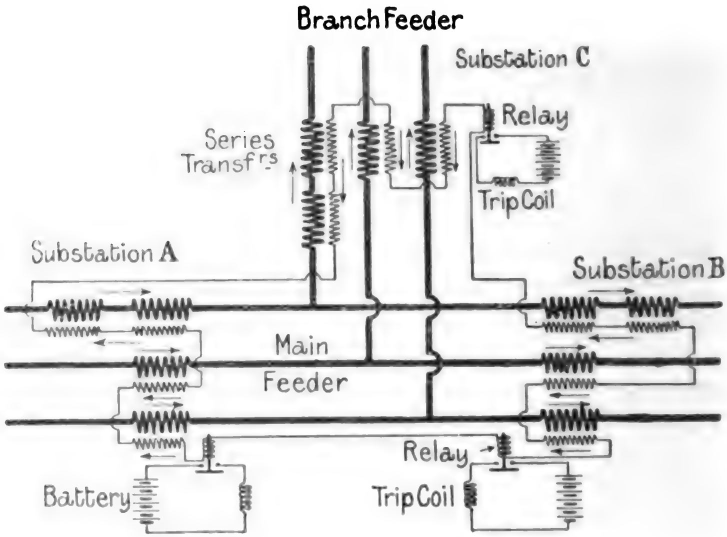


FIG. 21.

point supplied from this feeder) the entire section from which the branch is tapped will be cut off.

For the second method of protection (Fig. 17) it is important that the transformers have straight-line characteristics, even at heavy overloads, since it is only by this means that the voltage at the various points will be proportional to the currents and the sum of these voltages equal to zero. Consequently for such protection specially large series transformers should be adopted and rigid guarantees required with regard to the amount of current which can flow through the feeder without tripping the switches; also as to the amount of overload which can be taken through the branched feeder without disturbing the voltage balance at the three points. This method of protection is obviously much cheaper than treating the branching point as a sub-

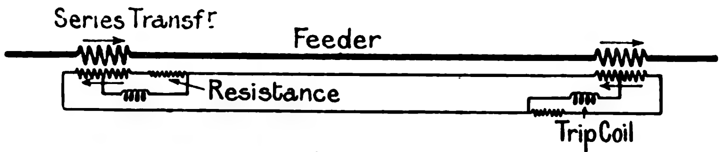


FIG. 22.

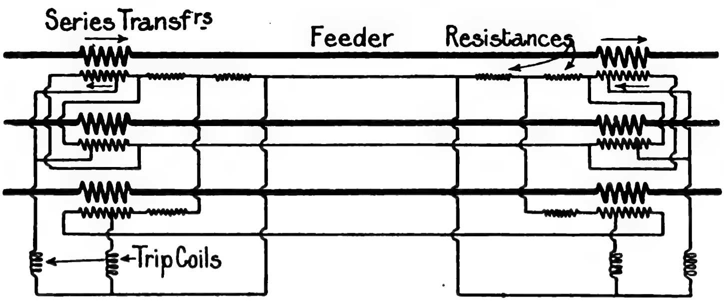


FIG. 23.

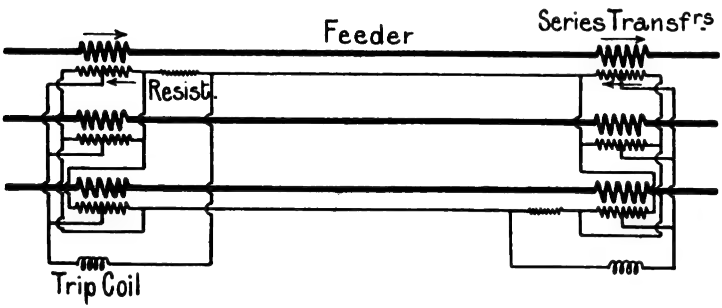


FIG. 24.

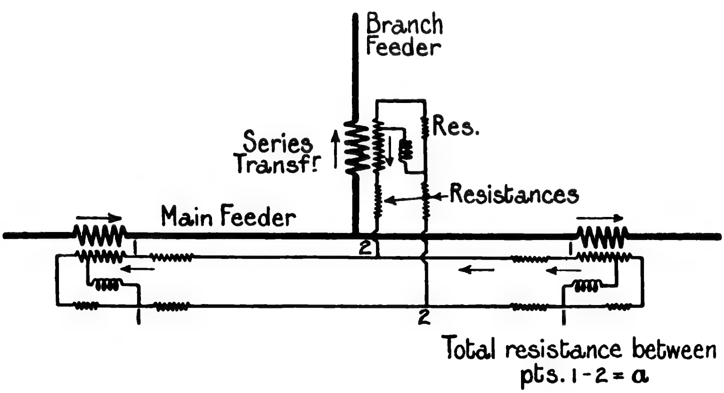


FIG. 25.

station (Fig. 18), since three sets of gear and the necessary housing accommodation for these are eliminated.

It is possible to use only 2 pilot wires for a 3-phase branched feeder with the balanced voltage system direct-current trip (see Fig. 21), although this arrangement reduces still further the sensitiveness with regard to the amount of fault current required to trip, and, continuing the comparisons for tripping current in Table A, 570 amperes would be required to trip with 6 miles of pilot wire. This corresponds to full-load current of 6,500-k.w. of plant and, as will be seen, greatly reduces the sensitiveness of the system—indeed, to a prohibitive value in the case under consideration—since with 2,000 k.w. of plant running and a fault to earth the fault current furnished might not reach this value, even if not limited by a resistance in the neutral.

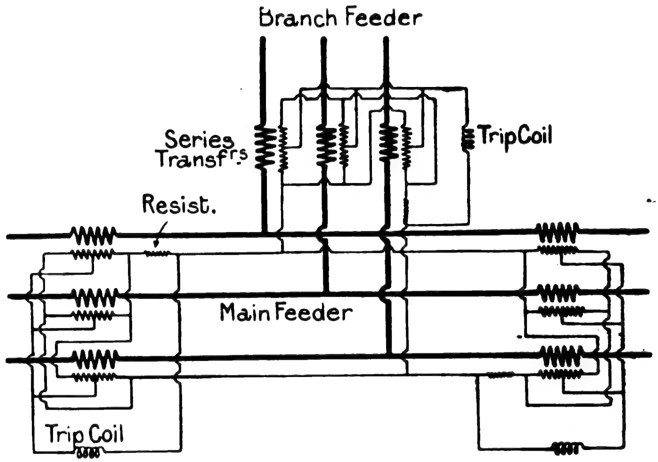


FIG. 26.

Using 3 pilot wires, as in Fig. 17, the remarks with regard to the necessity for straight-line characteristics still hold good, and the fault current required for tripping with one phase shorted to earth would be 287 amperes, which is a great improvement on the tripping current required if 2 pilot wires be used. Further, the safety against tripping due to capacity current is not reduced at all.

The balanced current system with resistances is well suited to the protection of branched feeders, and with this arrangement 2 pilot wires can be used, as shown in Fig. 26, due to the fact that three trip coils instead of two have to be operated; the fault current required for tripping is increased approximately 50 per cent.—*i.e.*, to 300 amperes against the 570 amperes for the balanced voltage system with 2 pilot wires and 287 amperes for the balanced voltage system with 3 pilot wires.

For all the above systems the sensitiveness can be improved by increasing the size of series transformer and the secondary voltages.

Parallel Feeders.—The protection of parallel feeders corresponds in many respects to the case of the ring main, although in general the conditions are much simpler. In the authors' opinion, the most effective method of protecting parallel feeders is by the use of the Merz-

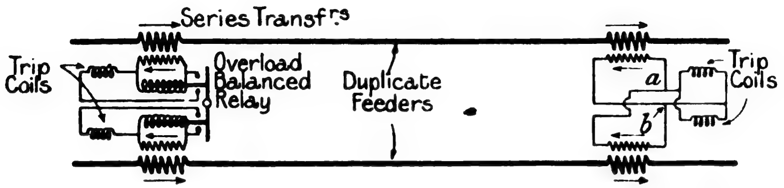


FIG. 27.

Price gear, and most of the data given above are applicable to this case.

Other methods of protection have been proposed, one of which is shown in Fig. 27. This, the authors understand, was introduced by the British Thomson-Houston Company. It is obvious that with the series transformers interconnected as shown at the sub-station end, no potential will exist between points *a* and *b*, provided the secondaries of

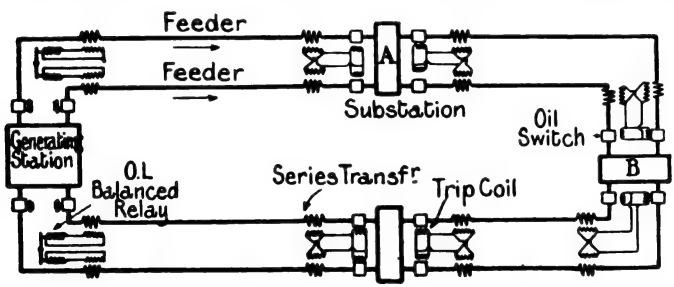
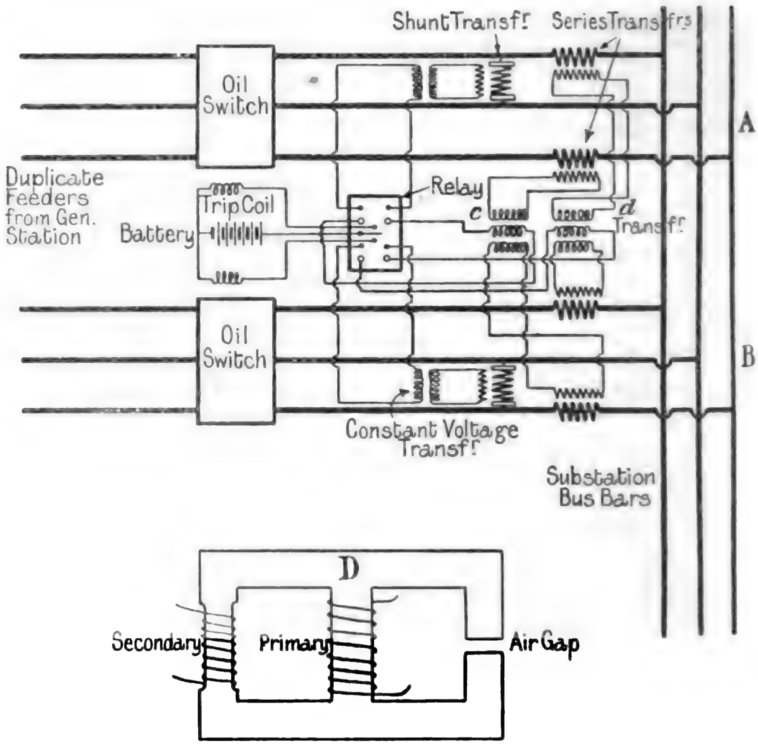


FIG. 28.

the two transformers are carrying the same currents; thus no current will flow through the trip coil connected across points *a* and *b* under normal conditions. If, however, a fault occurs in one of the feeders, then the currents in the primaries of the two series transformers flow in opposite directions, since the healthy feeder will feed into the faulty one and the secondary voltages of the series transformers will oppose one another, forcing current through the only available path, namely, the trip coil. It will be noticed, however, that this method does not discriminate as does the Merz-Price, in that both the healthy and the faulty feeders are cut off at the same time. If the arrangement shown

at the sub-station end is used at both ends, both feeders are, in case of fault, cut off instantaneously at both ends. If at the generator end the balanced relay shown is used, only the faulty feeder is cut out at this end, thus showing which feeder is faulty. Since the device cuts off both faulty and healthy feeder, it cannot be used as a discriminating device for two feeders in parallel, but if more than two feeders are running in parallel, then the device may be adopted between separate



Shape of Stampings for Const. Voltage Transformer.

FIG. 29.

pairs of parallel feeders, and in case of fault one pair of feeders is cut off.

This method of protection can be made discriminating by using such an arrangement as shown in Fig. 29, where A and B represent two incoming 3-phase feeders. The currents on these feeders are balanced against each other on separate transformers as in the magnetic balance system (the balanced current system could, of course, be used equally well). The extra windings on the balancing transformers *c* and *d* are led to a discriminating reverse-current relay. As

normally no voltage is induced in the extra windings, no current flows through the relay coils, and hence there is no deflection. On reversal of current in one feeder due to a fault in the feeder, current flows through the relay, which is deflected to one side or the other depending upon which feeder is faulty. This arrangement can be used at both ends of a parallel feeder and for parallel interconnectors, while the ordinary reverse-current relay cannot, but as the operation depends on the voltage of the system, as all alternating-current reverse energy apparatus must, it is not perfect, but there is no reason why it should not be as reliable on parallel interconnectors as the ordinary reverse-current relay on parallel feeders. This method was introduced by the Westinghouse Company in 1905.

In order to guard against the voltage failure in some measure, a special shunt transformer is adopted with the above arrangement; this transformer is shown in Fig. 29 D, and it will be seen that it is designed

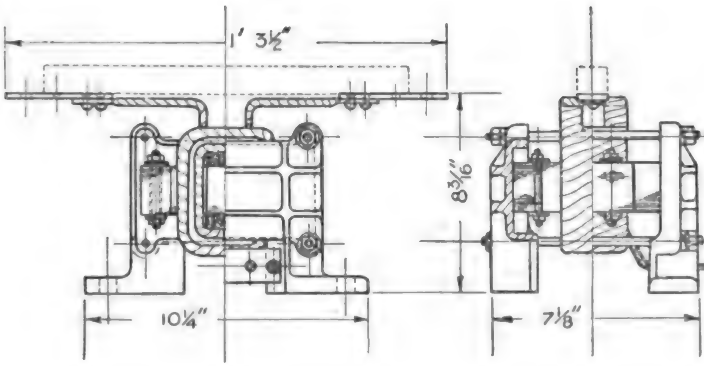


FIG. 30.

with three legs, on the centre one of which the primary winding is placed. The secondary winding is wound round the left-hand leg, which at the normal voltage is highly saturated. The right-hand leg is built with an air-gap. Assuming that at full voltage the flux produced by the primary coil divides equally between the two outer legs, then with a lower primary voltage the flux will divide so that a greater proportion than half passes through the leg on the left, since the permeability is greatly increased as the flux is reduced. Thus the voltage induced in the secondary winding will not fall so quickly as the primary voltage. There are, of course, limits to the holding of the secondary voltage in this manner, but it is obvious that an advantage is gained by its adoption.

Parallel Ring Mains.—The protection of parallel ring mains does not call for any special comment, as the methods of protection for ordinary ring mains can be applied in the majority of cases with the same success. It should be pointed out, however, that the arrangement

at the sub-station end of Fig. 27 can be applied with better success to parallel ring mains than to parallel feeders. For instance, Fig. 28 shows a system of parallel ring mains protected in this manner, and here, in case of a fault between sub-stations A and B, only the section between the sub-stations A and B is cut off, and a supply is still furnished to each of the sub-stations from one end. This is equivalent to cutting off two of the four feeders supplying each sub-station in case of fault in one of them.

In the above system it is necessary to have small auxiliary switches on the oil-switch mechanism to cut out the protective gear during switching operations, otherwise individual feeders cannot be switched on to busbars already loaded.

Further, when one feeder is cut out the other requires some additional protection, so that the systems are not self-contained, as is the Merz-Price system.

Apparatus for Merz-Price Gear.

Series Transformers for the Balanced Voltage Systems.—The majority of transformers have been constructed with air-gaps in the magnetic circuit, and the authors believe that most of the series transformers used for protection on the North-East Coast are either so constructed or have been provided with resistances in parallel giving them similar straight-line characteristics. The advantage of an air-gap in the magnetic circuit is that the impedance of the series transformers is greatly reduced, and when one transformer has to force current through the opposing series transformers, as in the case of "dead ended" faults, this reduced impedance is of great value in lowering the operating current. Series transformers without air-gaps can, however, be used, and are particularly applicable to low periodicity systems. The advantage of using series transformers without air-gaps is that the transformers are easier to balance and easier to keep in balance than transformers with air-gaps. Where such transformers are used it is advisable to connect them in delta in order to reduce the impedance of the pilot wire circuit. Where three points are protected, as in Fig. 17, transformers with air-gaps must be employed, as straight-line characteristics are essential.

Series transformers having only one primary turn have been largely used. This type of transformer is particularly suitable to the "balanced voltage direct-current trip" system, since the volt-ampere output of the series transformer required is very small. The transformer of Fig. 30 is that used by the Westinghouse Company and is of the ordinary series type, with the exception that a specially strong mechanical construction has been adopted to prevent alteration of the air-gaps due to rough handling. The dotted lines in the diagram indicate a resistance mounted across the primary of the series transformer, the object of this being to shunt high-frequency disturbances and prevent them passing through the transformer. The precaution

has been found unnecessary in practice, and most manufacturers have ceased to use such resistances.

Relays.—The relays are usually constructed in a very simple manner and call for little comment. The British Thomson-Houston Company's and the Westinghouse Company's relays are very similar in construction. In the Westinghouse construction (Fig. 31) the weight of the armature A is counterbalanced by an adjustable weight W,

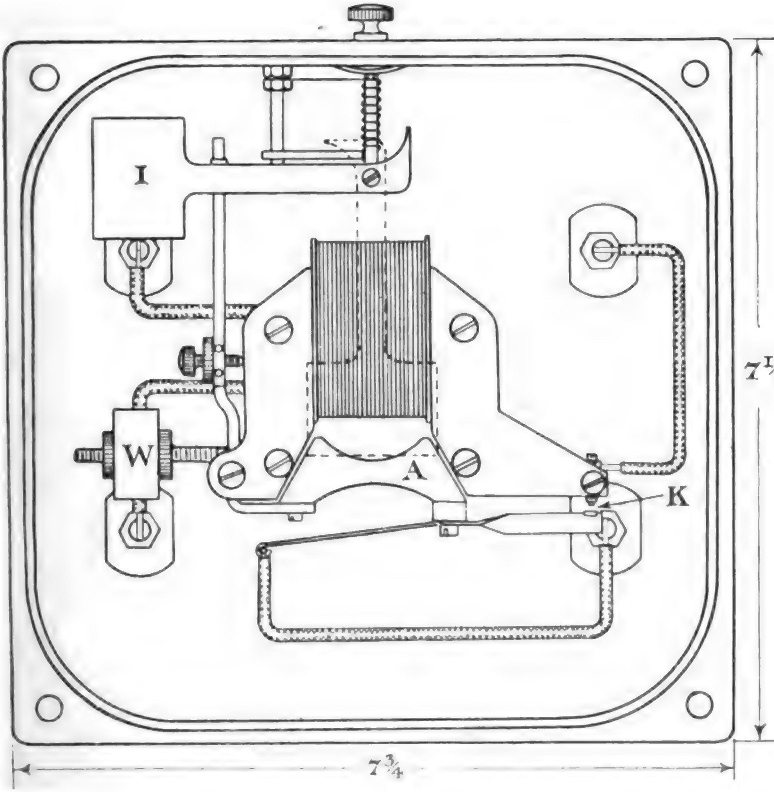


FIG. 31.

and the trip-coil circuit is closed at the contact K. On the relay tripping, the indicator I falls into the position shown by the broken lines, and this indicator denotes on which phase or between which pair of phases the fault has occurred. Such indication is not infallible, as, with a very heavy fault current, the relays on all three pilot wires may act; but in some cases the device is useful. The indicator may be returned to its normal position by means of the knob on the top of the case without opening the relay cover. In

the British Thomson-Houston Company's relay the trip-coil circuit is closed at two points, one at each end of the armature.

The Reyrolle relay (Fig. 32) differs somewhat in form from the two previously described, and is not arranged for automatically re-setting itself when a fault is cut off. This latter feature serves as an indicating device and renders a special indicator unnecessary, but in the form shown necessitates opening the case and re-setting the relay before the opened switch is closed again.

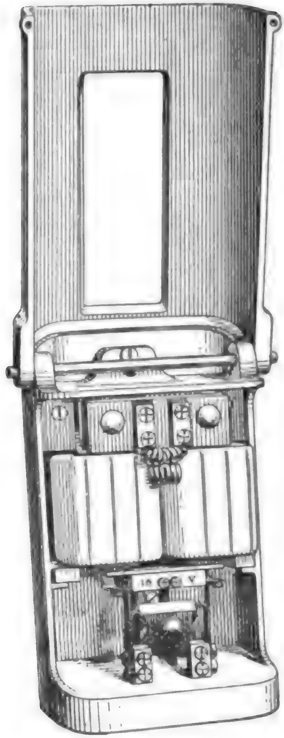


FIG. 32.—Relay, Open.

Relays which automatically re-set themselves have the advantage of breaking the battery circuit when the fault is cut off, and this prevents the battery from running down too quickly. When non-automatic re-setting relays are used, the battery circuit may be broken by an auxiliary switch on the oil-switch mechanism, but this introduces another link in the circuit which is liable to get out of order.

Conclusions.—1. The Merz-Price protective gear is the most satisfactory discriminative device at present produced, for transformers in parallel, for feeders in parallel, and for ring mains. The main advan-

tages are instantaneous operation and isolation of the faulty sections only, whilst it can be adopted for all conditions.

The gear renders possible freer lay-outs of the cable system than does any other protective gear, and due to its adoption more economical distributing systems may be used.

2. This protective gear can be applied in many ways, but the best form, owing to its simplicity and safety, is the balanced current system.

3. For feeder protection the system developed by the authors has all the general advantages of the balanced current systems, and is specially immune from trouble due to capacity currents in the pilot wires.

The use of only two pilot wires for 3-phase feeders, and the fact that no relays or batteries are required, give the system decided advantages over those hitherto used.

APPENDIX.

Method adopted for Calculating the Figures given in Table A for "Balanced Voltage, 3 Pilot Wires, Direct-current Trip."

Let the relays be designed to operate at 0·2 ampere, $4\frac{1}{2}$ volts, *i.e.*, 0·9 volt-ampere. Then with a factor of safety of 4, the capacity current at the maximum possible volts should not exceed $0{\cdot}2/4 = 0{\cdot}05$ ampere.

The voltage to produce this capacity current in pilot wires 6 miles long, with a capacity of 0·27 microfarad per mile is—

$$V = \frac{c \times 10^6}{6 p k},$$

where c = capacity current, $p = 2\pi \sim$, k = capacity in microfarads per mile, V = voltage;

$$\therefore V = \frac{c \times 10^6}{6 \times 2\pi \times 50 \times 0{\cdot}27} = \frac{0{\cdot}05 \times 1{,}000{,}000}{6 \times 2\pi \times 50 \times 0{\cdot}27} = 99.$$

This is the star voltage, and the voltage between outers—

$$= 99 \times \sqrt{3} = 171.$$

As there are two series transformers, one at each end of the pilot wire, only half the capacity current is supplied from each end, and hence the voltage of 171 may be doubled, giving 342 as the maximum volts allowable between phases to prevent danger of tripping due to capacity currents.

With an assumed ratio of 5 between the maximum possible volts and the volts induced in each transformer at full-load current, this latter voltage—

$$= \frac{342}{5} \times \frac{1}{\sqrt{3}} = 39{\cdot}5.$$

In case of fault, this voltage is consumed in forcing the tripping current through the relays, pilot wires, and series transformers, and is highest per transformer in the case of "fault to earth dead end." The load then consists of $1\frac{1}{2}$ pilot wires, 3 relays, and 3 transformers, including the one having the primary fault current.

Drop in pilot wires (react. drop negligible)—

$$=1\tfrac{1}{2} \times 8{\cdot}7 \times 6 \times 0{\cdot}2 = 15{\cdot}6 \text{ volts} = \text{ohmic drop.}$$

Drop in relays $= 4\frac{1}{2} \times 3 = 13{\cdot}5$ volts.

The drop in the transformers has to be figured, and is equal to—

Total reactive drop — drop in relays.
Total reactive drop... $= \sqrt{39{\cdot}5^2 - 15{\cdot}6^2} = 36{\cdot}5$
Drop in transformers $= 36{\cdot}5 - 13{\cdot}5 = 23{\cdot}0$
Drop per transformer $= 23{\cdot}0/3 = 7{\cdot}7$ volts.

The secondary voltage of the transformer, under these conditions—

$$= \sqrt{15{\cdot}6^2 + (13{\cdot}5 + 2 \times 7{\cdot}7)^2} = 33 \text{ volts.}$$

Thus the series transformers must be designed to give 33 volts secondary voltage when delivering 0·2 ampere with the required primary tripping current through their primaries, and to have an impedance of 7·7 volts when 0·2 ampere is forced through their secondaries.

Secondary output of series transformer at tripping—

$$= 33 \times 0{\cdot}2 = 6{\cdot}6 \text{ volt-ampere.}$$

Magnetising input for above output—

$$= \frac{33 \times 0{\cdot}2 \times 33}{7{\cdot}7} = 28{\cdot}0.$$

Total input (above added vectorially) $= 34{\cdot}0$ volt-amperes.

Thus for the gear to operate at 200 amperes primary current primary voltage $= 34/200 = 0{\cdot}017$ volts at tripping.

$\therefore$ Ratio of series transformer $= \dfrac{33}{0{\cdot}017} = \dfrac{194}{1}$.

Primary volt-amperes at full-load current $\dfrac{(34{\cdot}0)^2}{28} = 41{\cdot}0$.

Discussion before the Manchester Local Section.

Mr. P. V. Hunter: I believe I am correct in saying that so far as the practical application of this gear is concerned neither of the authors has had the advantage of an extended experience, and, to one who has watched the commercial working of a large system equipped with balanced protective gear, their grasp of the problem in its practical details is remarkable. First, I should like to point out, in connection with the design of balanced protective gear, the pressure rise which takes place on the secondary side of the current transformers due to severe overloads occasioned by faults on the system. This overload comes on all the apparatus between the fault and the power station and causes a rise in secondary voltage on all protective current transformers through which it passes. From Table A it will be noticed that this pressure may reach 600 or 700 volts between the terminals of the current transformer. This condition is entirely new to current transformer working, and unless the secondary winding is specially insulated to meet it, a breakdown will occur between turns. In general, this breakdown will not be discovered at the time it occurs, because it does not sufficiently alter the ratio of the current transformers to make them operate on ordinary loads. When, therefore, a second fault occurs elsewhere on the network, the protective gear on the faulty section operates, and also that in which the current transformer secondary had previously broken down. This may result in shutting down a large part of the network. The trouble is of course very easily guarded against, once it is known, by means of additional insulation between turns on the secondary winding. Secondly, it is of great importance to design balanced gear for fault conditions, and not for what we ordinarily understand as full-load conditions. It is of the utmost importance that the balanced protective gear should not break down under any rush of current which may conceivably occur during a fault; in fact, any protective gear installed on a mains system should be capable of being run safely for an appreciable length of time under the maximum momentary fault conditions; that is to say, if the maximum fault current is 10,000 amperes under a short circuit, the balanced protective gear should be capable of being safely run at this current, and it is this current which the designer should have in mind. If ordinary current transformers are designed for the comparatively small load represented by the full load of the apparatus protected, they are likely to explode under extremely severe fault conditions. I am afraid that those who have not had much experience of the balanced protective gear and the variety of ways in which it can be arranged will be very confused with the large number of diagrams shown. The only satisfaction I can give them is that the authors might have made things infinitely worse. I have never attempted to count the ways in which it is possible to connect up protective apparatus on the Merz-Price system, but the number runs into hundreds. For the information of those interested I may say that so far as I am aware the only arrangements used in com- Mr. Hunter.

Mr. Hunter. mercial service on any reasonably large scale are shown on diagrams 9, 13, and 17. These three arrangements have been used very freely, and I believe the transforming apparatus protected exceeds 50,000 k.w., and the miles of high-tension cable are anything up to 500. Returning to the question of the number of balanced protective gear arrangements, it is a most interesting fact that whenever any one meets the protective gear for the first time he always sits down and works out an arrangement of his own. The authors' contribution is shown in Figs. 21 to 26. They suggest that Fig. 24 is an improvement on Fig. 13, and they give their reasons on page 687. I hope no one will dispute their claim for this arrangement, as it would be of interest to see it developed. I note that on page 688, paragraph 4, it is stated that a break in the pilot wire immediately results in the feeder being cut off. This is of course only true if there is sufficient current in the feeder to operate the relays, and as this current is usually full-load current, it is probable that the feeder would not be cut off in the event of a break in the pilot, and perhaps not until a fault occurred elsewhere on the system producing sufficient current to operate the relays. I also notice from paragraph 2 on page 687 that the authors object to the tripping batteries. I may say that these are put in for entirely different reasons from those which the authors have in mind, and that even were direct tripping possible with the voltage-balancing gear it is improbable that it would be used to any great extent. To my mind the most serious objection to the arrangement which the authors recommend is the number of parts which have to be balanced. In Fig. 23 there are eighteen, and in Fig. 24 there are fourteen, whereas in the ordinary voltage-balancing gear there are only six parts to be balanced. Referring to Table A, it is unfortunate that so far as column 1 is concerned the figures for the voltage-balanced arrangement are calculated on entirely theoretical apparatus. It will be noted that the primary input at full load is given as 41 volt-amperes. On the north-east coast, for feeder protection, this system of balancing is used exclusively, and the actual primary input of the 6,000-volt transformers is 5 volt-amperes, not 41. I do not suggest that this small figure has been adopted on account of the saving of energy, nor is it due to the fact that with the small output the current transformer can have a bar primary. The real reason why this protective gear for voltage balancing has an output of 5 volt-amperes is that it is designed to work continuously with the maximum fault current. I do not think any apparatus which the authors put forward would work under these conditions for a minute without using a large amount of material in construction, thus making it extremely cumbersome and expensive. In conclusion I should like to emphasise the fact that in designing protective gear the great point is to forget ordinary full-load currents and design absolutely for the particular maximum fault conditions.

Mr. Clothier. Mr. H. W. CLOTHIER: As it was my privilege six years ago to be associated with Mr. Price in the design of "Merz-Price" protective systems, I am in a position thoroughly to appreciate the value of the authors' remarks, and I agree entirely with their conclusions that this

Mr. Clothier.

system of protection has many advantages. In support of this opinion I have, thanks to the courtesy of Mr. Lackie, of Glasgow, a piece of cable which developed a short between two phases. Fortunately it was suitably protected, and in consequence was cleared so quickly that there was only a very small hole burnt in the cable. It is interesting to note that even the outer dielectric was not pierced by the arc. Incidentally this example is of particular interest at the moment in view of the necessity now under discussion of clearing faults in mines so quickly as to avoid flashing external to the cable. It is a significant fact that similar cable faults have occurred in places where the balanced protective gear was not installed, and such faults have occasioned complete shut-down for lengthy periods. Seeing that the authors have shown a drawing of a transformer, I may be allowed to describe details of the transformers installed on the 6,000-volt networks in Newcastle. The construction shown in Fig. A is probably the simplest form of transformer devised for use with the "Merz-Price" system. The primary, consisting of a straight through conductor, lends itself

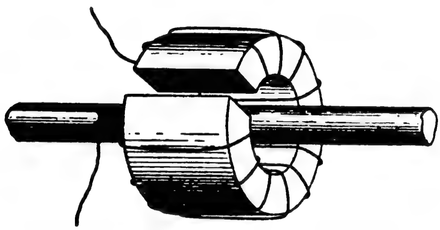


FIG. A.

to perfect insulation. Moreover, with this construction every transformer can be balanced with a standard at many times its full-load current. For such purposes it is possible to thread a solid copper bar which will carry 5,000 or 6,000 amperes, whereas to carry such heavy currents through a transformer with primary turns, owing to the limited section of the copper, would be difficult. The core is of a circular type, and has an air-gap as shown on the sketch. The primary input is less than 5 volt-amperes at full load, as compared with the authors' transformers of 41 volt-amperes and 125 volt-amperes. The air-gap affords a ready means of adjustment, and in practice these transformers are accurately balanced with the standard in this way. The transformer differs from that shown by the authors in that it has a straight-line characteristic up to twenty to thirty times full-load current, thus, in contradistinction to the authors' design, it is suitable for use with tees. It is satisfactory to note that, although there are at least 1,000 of these transformers in everyday use, there has never been any failure either in the insulation of the primary or between turns on the secondary. With regard to the capacity current in the pilot cable, I admit the disadvantage of a transformer having a straight-line charac-

Mr. Clothier. teristic up to twenty to thirty times its full-load current. On the other hand it must be borne in mind that a cable 6 miles long has such a resistance as to put a limit on the amount of primary current which can pass through it in the event of a fault occurring. Therefore the question of capacity current only comes into consideration for short lengths of cables near to the generating plant, and in such cases the capacity current in the pilot is negligible because the cables are short. The relay shown on Fig. 32 is the first design of relay made for this work in this country. Many engineers prefer not to rely solely upon a single contact to trip their switches, and, in order to meet this requirement, this relay is made with a small weight, which is released after the first contact is made by the armature. In falling, the weight hammers home a contact which is in parallel with that made by the armature, and thus adds an element of security besides avoiding sparking at the relay contacts. The authors are somewhat misleading when they infer that these relays do not automatically re-set themselves, as it is only necessary to remove the supplementary contact, and then, like the authors' design, the relays will automatically re-set themselves. It is more correct to say that the relay on Fig. 32 possesses an advantage over the relay on Fig. 31, in that the former can be made automatically to re-set itself or not, as preferred by the user. I would also suggest that the light armature on the relay to Fig. 32 is better than the heavy armature and balance weight on Fig. 31, as the inertia of the latter would, as compared with the former, tend to retard the instantaneous action of the relay. The authors mention the necessity of opening the case in order to re-set the relay. It should be noted that opening the case is a very simple matter in the type of relay illustrated, although as a matter of fact this and other types of relays are re-set by a small button placed outside the case. With regard to the authors' proposals, it is as well to correct their impression that current balancing has not been used in practice in conjunction with feeder protection. There are several instances of current balancing for feeder protection in the Newcastle district. The system is known there as neutral-wire balancing, but this system was abandoned in favour of electrical balancing. The proposal shown in Fig. 24, which eliminates relays and the auxiliary trip, is particularly interesting, and would be an improvement if it could be arranged without involving an excessive primary input to the series transformers at full load; but on page 691 the normal input of these transformers is given as 125 volt-amperes, and although six only are shown on Fig. 24, there are really eight of these proposed in the scheme. When compared with the six transformers, with a primary input of only 5 volt-amperes each, required by the E.M.F. balancing as used at Newcastle, the waste of energy in the transformers in the authors' proposal represents in the long run a much more expensive item than the initial cost of relays and batteries. The saving of one pilot wire claimed is also possible, when necessary, with E.M.F. balancing. The reason that no attempt has been made in the Newcastle district to eliminate the relays and auxiliary trip is that it has

been considered necessary to work the tripping mechanism of the switches periodically. The authors, I believe, admit the possibility of the switches sticking. It is therefore a common practice to trip the switches at regular intervals, and this operation can be most conveniently carried out when relays with auxiliary trips are used. In conclusion, therefore, whilst giving the authors the credit due to them for their most ingenious proposal, I think there is much left for them to do before they can lay claim to having materially advanced the subject of design, but at the same time much good is bound to result from the open way in which they have brought their proposals forward. Mr. Clothier.

Mr. E. B. WEDMORE: I consider that the commercial merits of the Merz-Price system are not yet recognised as they should be, and perhaps in time to come we shall recognise the debt the industry owes to the makers of this protective gear. It might be of interest to state that the circulating-current system shown in a number of the figures has been independently developed by the B.T.H. Company, who have used it extensively for a number of years. The same Company have had under consideration the advantages of the circulating-current system as applied to feeder protection, and have developed methods of compensating for pilot-wire drop and capacity current in the pilot wire, similar to those illustrated, and I believe they have also applied for patent protection. I would like to emphasise the importance of the question of excessive heating in current transformers, referred to by Mr. Hunter. It is not generally realised what very high temperatures can be reached in the fraction of a second required to clear a fault in cases where the current transformer primaries are designed to carry normally a small fraction of the total output of the plant, but during a fault have to carry many times this current. The heating effect, of course, increases with the square of the current, and I have known of several instances where current transformers have exploded violently under such conditions. I appreciate the advantages of the circulating-current system for feeder protection, and would add that on large systems it is quite practicable to obtain the full advantages of the single turn primary-current transformer and the direct-current tripping device, by employing sensitive relays in place of direct-acting trip coils. I believe that this system has a great future before it. After some experience in the balancing of transformers, I am satisfied that an adequate balance can be readily obtained under this system, and the apparatus made more sensitive owing to the ready manner in which capacity-current difficulties are overcome. The systems shown in Figs. 27 and 28 are typical of a number of devices I have developed for different service conditions, and I may say that the defects the authors have found in the arrangement shown in Fig. 27 are due to the omission of certain items from the diagram. In order to make the arrangement discriminate, it is only necessary to add reverse-current relays normally short-circuiting the respective trip coils. The employment of the cross-connected current transformers ensures that there would be no tripping current in the case of a Mr. Wedmore.

Mr. Wedmore.

surge, whilst the employment of the relays makes certain that only the defective feeder would be cut out on a fault occurring. I have sometimes regretted that Messrs. Merz and Price had developed their selective system as soon as they did. Had they turned their attention to the improvement of reverse-current relays, I feel sure that great advances would have been made in that branch of the art. Owing to the relatively high cost of their system, it has been necessary to find cheaper methods of dealing with the problems met with. The reverse-current relay of the present day is a very different device from that which Messrs. Merz and Price have condemned. The relays used in the system above referred to were designed to give large forces operating with extreme rapidity on small currents, even at quite low voltages, and would operate on far smaller current values than could be considered in connection with the Merz-Price system. This question of rapid operation is very important for feeder protection, as faults due to puncturing of insulation develop relatively slowly, and sensitive relays would clear them with a minimum of disturbance of the system. About two hundred of the relays referred to are now in use on generators and feeders, and have not only met all service conditions, normal and abnormal, but have been very severely tested by some of the users, and by bad faults in service. There is a large scope for protective devices suitable for use only on parallel feeders, as the latter are very extensively adopted, and are likely to be so. Whilst the system at Newcastle of employing single feeders and interconnectors seems to be admirably adapted to the rather special conditions existing there, it is found that in a large number of cases the employment of parallel feeders gives greater economy in cable. For example, in the typical case of a generating station surrounded by three, four, or even five sub-stations, a little elementary geometry will show that less cable is required for the parallel feeder system than for furnishing single feeders with interconnectors. In this connection I would like to refer to a method of distribution eminently adapted to small industrial towns where customers are small power users and capital cost an important consideration. In such cases the consuming points cannot be readily predetermined, so that the most economical ring-main system could not be laid out. Moreover, owing to the necessity of confining cables to available streets, it would often be impossible to adopt the theoretically best system of conductors. The cost of obtaining way-leaves and of opening up additional roads is also a consideration. In such cases a parallel feeder system can be employed with advantage, the feeders being connected together only at the generating station and each customer furnished with switches for connection to either system, but arranged so that connection could not be made to both systems at once. The expenditure required for the employment of discriminating gear on such a system would not be justified, but as the feeders would all be open-ended, one might employ with great advantage leakage protective apparatus at the generating station alone. I refer to the balanced core system of leakage protection,

by which individual feeders might be disconnected instantaneously on leaks developing, representing a small fraction of normal-load current. This arrangement has great advantages. An earth resistance of high ohmic value may be employed, ensuring that the fault currents are limited to a fraction of normal-load current. The employment of earthing resistances of high ohmic value removes all difficulties which may be experienced in some cases, due to currents circulating between the generators, and greatly simplifies the problem of earthing the neutral. There is yet another advantage which has not been fully appreciated. It is often found that a heavy fault so distorts the voltage triangle at the generating station that individual induction motors and other apparatus in all parts of the system feed back to the fault and cut themselves out of service. This feature cannot be directly dealt with by the employment of the Merz-Price system of protection, but by the employment of a leakage system and a high resistance to earth the trouble may be eliminated. With very few exceptions, faults develop first as faults to earth, so that on this system serious disturbances are practically eliminated. The disconnection of faulty sections without the necessity for the development of heavy short-circuit currents relieves the system also of the inevitable static strains due to violent changes of current value. Mr. Wedmore.

Mr. A. E. McKenzie : To those responsible for the maintenance of an uninterrupted supply of electricity from a power station, the choice of the correct protective gear to instal is of the utmost importance. On the Manchester system, so far, there is no balanced protective gear on the feeders, although there are ten sets on order. I am greatly surprised that all the previous speakers have agreed, by their silence, in recommending that this gear should not be used for the protection of generators. In Manchester there are two 4,000-k.w. generators which have been protected by this gear for the last two years. Previous to its installation we were subject to a great deal of trouble on these alternators through faults starting between turns in the same coil, and subsequently developing to earth. When the generators were re-wound the balanced protective gear was installed, but it has not yet been called upon to operate, as no faults have since occurred. I appreciate that this system cannot be used for the protection of generators against loss of field, but how often does a generator lose its field? I have had many years' central-station experience, but have never yet known a generator totally to lose its field. I do not consider it necessary to instal an automatic device which will always cut out a generator when loss of power takes place, but think that this can safely be left to the discretion of the switchboard attendant. No automatic devices that we have tried at Stuart Street, Manchester, have given satisfaction under all conditions, but we consider that the balanced system has the most advantages. At the present time our 6,000-k.w. generators are connected solid to the bars, but Merz-Price gear is now on order, and will shortly be fitted to them, and we believe that it will meet every condition that is necessary. I do not consider it essential that Mr. McKenzie.

Mr. McKenzie. generators should always be cut out immediately a fault occurs between different parts of the same phase, having on several occasions found coils welded together when cutting out for rewinding. In my opinion the alternative to the Merz-Price protection for generators is not to protect at all. I agree with Mr. Clothier that it is advantageous to have the tripping coils operated by an auxiliary circuit, so that they can be tested regularly. The relays on the generators at Stuart Street are frequently closed to open the switches when the generators are being taken off load, to see that the gear is in working order. Of course, most of the high-tension feeders in Manchester were run before the balanced system was known, but pilot wires have been laid in all the cables recently put down. Where duplicate feeders run to the same busbars in a sub-station, relays are installed, and have always answered very well. Some years ago, when it was not so well known how long it was possible to run on a high-tension fault, relays were put in at Stuart Street which could be adjusted to 20 seconds. These relays are now set absolutely instantaneous. When the instantaneous setting was first tried, it was anticipated that when faults occurred on the low-tension network the momentary rush of current would open the main feeder breaker at the generating station, but they have been set this way for about two years, and, so far, no trouble of this kind has been experienced. The relays are set to operate at twice the normal full load of the feeder, and on some occasions pieces of 3-core 0·15 cable, lead covered and armoured, 1 ft. long, have been burnt away. I was therefore very interested to notice the piece of high-tension cable which Mr. Clothier produced, showing the very slight damage that had occurred to cause the balanced protective gear to open the feeder circuit breaker at the Glasgow station.

Discussion before the Birmingham Local Section, January 11, 1911.

Mr. Railing. Mr. M. Railing: On account of the tremendous spread everywhere of electric application in industry and private life, it has of late become increasingly necessary to use all possible safeguards. The protection of life and property has become more necessary and more difficult; more difficult on account of the extensiveness of the problem, the large number of users and of producers; more necessary not only because of the value of life and property, but also because every neglect of safeguard in the eyes of numerous competitors means a retrograde step for our industry.

Mr. Taylor. Mr. A. M. Taylor: The authors pay considerable attention to the minimum tripping current; but whether an oil-switch clears a fault successfully or otherwise appears to me to depend more on the oil-switch than on the relay. The question whether one relay which commences to operate with 250 amperes is better than another which requires 500 amperes seems unimportant, in view of the fact that a short-circuit current might reach a value on a large system (such as

that in a big town) of, perhaps, 10,000 amperes in the $\frac{1}{100}$ part of a second, whereas the oil-switch would not clear a fault under, perhaps, $\frac{1}{5}$ to $\frac{1}{10}$ of a second. Long before the relay itself had operated, much less the switch, the current would have reached a value several times in excess of the 500 amperes above alluded to. It may, perhaps, be worth mentioning that I have designed a switch which will, I estimate, open a circuit in the $\frac{1}{300}$ part of a second, or will, if preferred, simply cut down the current, so that a dangerous value is never reached, breaking it as the wave passes through zero in the manner indicated in Fig. B. With regard to the question of the protection of feeders by the Merz-Price system, it seems that such a system is highly desirable, in spite of the limitations of the switches at present employed; but, where a large underground cable system is already laid down in a town, it is a very serious matter to consider the opening of the streets for the purpose of laying the pilot wires needed in conjunction with the Merz- Mr. Taylor.

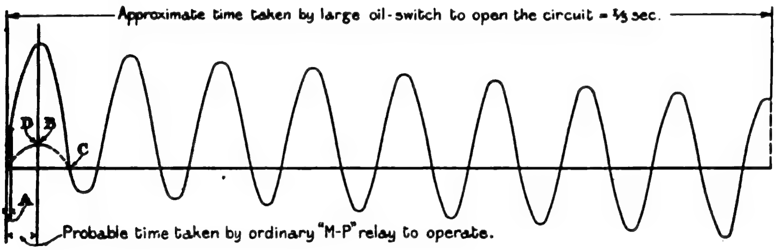


FIG. B.

A. Time taken by special switch to open circuit if current unaltered.
B. Current in special switch if account taken of insertion of resistances by same.
C. Point of break circuit by special switch.
D. Point of break circuit by special switch if required.

Price apparatus. With reference to the remarks at the foot of page 685 and the diagram Fig. 19 on page 693, I am not sure that the proposed extra transformer will solve the difficulty. While it would be efficacious in the case of a short circuit between phases (1) and (3), or (1) and (2), it will not protect against a short circuit between phases (2) and (3). With regard to the question of pilot wires, I have considered the possibility of doing without these in certain cases by introducing a discriminating system depending upon the momentary drop of potential on the occurrence of a fault current. Any ordinary reverse-current relay is, of course, useless for this, as all the relays on the one side of the fault would act together; but if a relay could be devised which would only respond to the position on the ring at which the maximum drop occurred, and which was unaffected by the passage of ordinary "load" currents (no matter in which direction they flowed through it), and in which, moreover, the action was the more positive the greater the drop in E.M.F., then, it seems to me, protection might be obtained, even on a ring main, without any pilot wires. I believe it is possible to

Mr. Taylor. devise such a form of relay. I believe it would also be possible to discriminate between consumers who were only a quarter of a mile apart, and, if necessary, even closer than this. For longer distances the problem becomes correspondingly more easy.

Mr. Chamen. Mr. A. D. CHAMEN: A great deal has been said and written lately with regard to protective gear, but, considering the importance of the subject to power station or supply engineers, I do not think the subject has been overdone. My experience is that engineers looking at contrivances of this kind often say: "This is extremely pretty on paper, but how is it going to do us any good?" They are now, however, gradually coming to see that the Merz-Price gear is not merely something nice to have, but also something necessary for the satisfactory working of their system, and are installing more and more protective gear once they have had experience with it. The authors of the paper have gone very thoroughly into the subject; they have cast about to try to make improvements on existing methods, and they claim to have succeeded in doing so. Here I want to criticise one or two points. First of all, the authors make a point of doing away with the relays and batteries. They look upon that as an advantage, but I am afraid I do not agree. My reason is that it is very necessary to test the switchgear for operation. Of course it must be realised that when Merz-Price gear is installed on a system it is far more necessary to keep it in proper repair than the ordinary overload gear, for if a switch shall stick or, for some reason or other, the apparatus should fail, the fault falls back on the generators, and unless there is some overload device the result is a complete shut-down. Hence it is of vital importance to keep the Merz-Price gear in order. I would be glad to know how the authors propose to carry out periodic tests with an alternating-current trip. If a battery and relays are provided it is quite easy to test the feeder switches one at a time by tripping each relay with the finger and to see that the switch opens satisfactorily. In my experience switches failing to trip is the most frequent trouble. I do not say that it is the fault of any particular switch; it is an inherent fault in any oil-switch, but if tested at short periods any failure is checked in time. The second point that they make is that they use only two pilots. I can only say that with the electrical balancing system, and by using air-gap transformers, exactly the same arrangement is made. Only two pilots are necessary, exactly in the same way as with the current balancing. The third point made by the authors is that this gear is easier to maintain and keep in order. I am not so sure about that, as instead of relays we have resistances, and we have also an extra transformer at each end. The authors say that it is not necessary to construct their transformers carefully. I can only say of the air-gap transformer that it is easy to construct and there is no difficulty with balancing. Every transformer is carefully tested during construction, and this is a very simple matter. I have never heard of a fault or failure of an air-gap transformer either with the insulation or with the balancing. I do not see how the first cost of the authors' system can be any less than the electrical balancing

system. They use extra transformers and resistances against the relays and set of batteries. Of course the point as to whether the transformers are more costly or not is one I cannot answer. One would naturally think they would be, as they have to have a greater output. The firm who have installed most of the apparatus in this country are still using air-gap transformers and electrical balancing for feeders, but not for transformer protection, etc., as this is a different problem. It has the advantage that it may be used on any system, and no alteration is necessary if the cable is teed off. It is an absolute standard for all conditions. Of course, there is a limit to the number of tees on one cable that can be dealt with whichever system is used, because the connections get complicated, and the impedance considerably increased with each tee added. It is not desirable to have more than two or three on one cable. As for capacity troubles, I may say that this has been overcome entirely in practice. The patentees considered current balancing and alternating trip for feeders before anything was really settled. They thought it was well to abandon it in favour of the battery trip. A great point has been made by the authors as to sensitiveness. They claim that the current balancing with the alternating trip arrangement is more sensitive than electrical balancing with air-gap transformers. That may be so, but as a matter of fact the short-circuit current on any part of a system is very much larger than any of the figures given in the table. It is therefore unnecessary for the apparatus to be very sensitive. I may say also, and this will answer one of Mr. Taylor's questions, that whenever a fault has been cleared by the Merz-Price gear it has scarcely been known on the system that there has been any fault. In some cases a slight kick has been noticed, but never any suggestion of synchronous plant getting out of step. The reason is that when a fault occurs in a cable the protective gear cuts it out before the current has reached a very high figure. Mr. Taylor, on his diagram, shows a current ten times the full load, which is more than the authors say will generally take place with the dead short circuit owing to the cable resistance, but nearly every cable fault starts with a small current, and does not develop to its maximum at once. That is the reason faults have been cleared before there has been any severe shock on the system. Of course, if a pole line is being dealt with, if two phases come together, there is a dead short circuit, and the maximum possible current is reached at once. The authors' current balancing requires two resistances in the pilot circuit to ensure proper operation. This resistance requires adjustment, and I presume that if a feeder has to be cut in the middle for additional connections (say another consumer) this resistance has to be readjusted and the whole lot balanced again. With electrical balancing that is not the case. One simply connects up a fresh set of current transformers on each side to balance with the old transformers. With regard to Fig. 26—I may be wrong—but on the face of it there appears to me a doubt as to whether this would work. Supposing a fault were to occur on another cable and the current feeding it had to enter the teed cable at two limits and pass out

Mr. Chamen.

Mr. Chamen.

on the third, obviously the current in the third limit will be greater than that in either of the other two. That means that the current transformers will have to work on different parts of their curve. Now, these transformers are partly E.M.F. and partly current transformers, and it seems to me that unless they are huge they will not be able to give equal current or equal potential; that is to say, the transformers will have to be large enough to overcome the impedance of the pilot circuit and other transformers, trip coils, etc., in the circuit, without losing their ratio at all. The authors have mentioned some other types of protection, but I do not think they are real competitors to the Merz-Price gear. Mention is made in the paper of transformer protection, stating that when tappings are made on the main transformer to obtain slightly higher or lower voltage, it is also necessary to make corresponding tappings on the current transformers to insure a good balance. In practice this is not necessary for tappings, say, 5 or 7 per cent. variations from normal. Return now to the question of the bad effect on the system if the Merz-Price gear should not operate. With the Merz-Price gear one cannot or should not do away altogether with overload relays. There should be certain number of time limits put in in different places, but they should be put in at only a few places, carefully thought out and proper time limits arranged. A safe thing is to start at the generating station by putting time limits on every feeder, then if the network is large and anything like the North-East Coast systems, instantaneous overload relays can be fixed at certain switching centres, whose function would be automatically to split up the system into various smaller sections, but still keeping duplicate supply to every sub-station. In the case of a bus-bar fault, which is not dealt with by the protective gear, this limits the region of trouble to one district only. It is wise to take every system by itself and study the requirements and arrange the protective gear to suit it; it must be treated carefully on its own merits.

As regards reversed current relays, I do not think much can be said in their favour. They are frequently used for generators. I think I am right in saying that if a generator loses its field it does not follow that reverse current passes into it. The power factor can drop below 50 per cent. and still be in the same direction as regards the potential, in which case a reverse relay will not operate. I see that the authors have made a correction in reading their paper; they say that they do not advise Merz-Price gear *only* for generators, and that makes a great deal of difference. Merz-Price gear on generators is very useful where two or more generators are running in parallel. Of course, it is of no use whatever if only one is running. A point is made by the authors that the gear will not work with a fault between turns such as is caused by the burning-out of an armature coil. That is not a very important point, because smoke will generally be seen coming from the alternator before any appreciable current is taken by that phase, and there is plenty of time to switch the machine out of circuit. Such a fault generally develops into a short circuit between phases or to earth, and

as soon as this happens the protective gear cuts the machine out of circuit. Further, if a generator loses its field, this does not constitute a short circuit on the remaining generators, but it will run as an induction motor with very bad power-factor until switched out. So none of the faults which can occur to a generator which will not operate Merz-Price gear, can be dealt with any better by any other device, while the Merz-Price gear has the advantage that it will instantly switch out a machine which develops a fault between phases or to earth. I would prefer to protect generators with Merz-Price gear and with nothing else. Obviously, overload gear is unsatisfactory, as in the case of a short circuit on the mains the feeders should be switched out and not the generators. It may be interesting to give a little experience I had just lately in South Wales, where I have been installing protective gear on two colliery power schemes; the mains are all pole lines. The problem is not quite the same as with cables. Anybody who has had experience of pole lines knows that, as a rule, if the insulator or binding breaks and the phase falls on the bracket arm, the small current passing simply sets fire to the pole. Several cases have occurred where the pole has been set fire to in that way. Sometimes the wires have become heated, drawn out and broken, and the two broken ends have lain on the ground still alive. The current was so small to the earth connection that it was not enough to trip any kind of overload protective gear. Now when Merz-Price protective gear is installed, a lead-covered pilot is suspended from pole to pole, and is held up with a steel catenary wire. This steel wire is connected to the bracket arms on every pole, and so the earth wires on every pole are joined in parallel, this in itself insuring a fairly heavy return circuit for the fault current. Also the catenary wires and the lead covering are connected to substantial earth plates at every substation and at the generating station, as well as being directly connected with the neutral points of the generators. The result is that when any such fault occurs as is described above, there is ample current flowing through the fault to operate the Merz-Price relays. These installations have proved to be perfectly satisfactory. Mr. Chamen.

Dr. M. Kloss: The paper with all its various diagrams furnishes a very good proof of the flexibility of the Merz-Price system. I think that the system is one of the best ideas that have been developed in the electrotechnical industry, especially from the point of view of which Mr. Railing has spoken: that of the importance of protection in electrical circuits and apparatus. Perhaps the greatest advantage of the Merz-Price system is its capability of cutting out a fault during its development. I do not think any other system will do that. If an ordinary overload relay is used, of course it must be set sufficiently high to allow ordinary overloads to pass, if they only last a short time. On the other hand, if a fault begins to develop, it will not act so long as the increase in current keeps within the limit for which the relay is set. That means the relay will generally allow a certain time to pass before it acts, so that a real short circuit will occur. Further, take the case of Dr. Kloss.

Dr. Kloss. no-voltage relays. These do not fully act until the voltage has dropped to an undesirable amount. Either of these old schemes, in fact, will allow a dead short circuit actually to develop before they will act. The Merz-Price gear, however, will discriminate, as has been pointed out, and will cut out a feeder or any other faulty part of the apparatus even if there is no reason for a dead short circuit to be caused by the apparatus at the power station. It will cut out the faulty apparatus during the time taken for the faults to develop, and I think that it is a great advantage because it enables one to repair it and put the whole thing right again before any great damage is done. I should like to ask whether any experience has been gained either by experiment or by actual practice with reference to higher harmonics in such cases as those given in Figs. 8 and 9. It is well known that alternators not producing a true sine-wave E.M.F. will set up circulating currents of the third harmonic if connected in delta. I should like to know whether the corresponding secondary currents of the transformers are likely to operate the trip coil. With reference to Mr. Taylor's remarks on a switch designed to cut the current off in a fraction of a period, it is true that by this means the danger of mechanical stress set up in the windings of machines and apparatus, and also the chance of overheating due to the enormous value of short-circuit current might be reduced. Still it should not be forgotten that at the same time a new danger is introduced by the rise in potential, which is proportional to the rate of change of current. If the cutting-out would commence just at the moment of maximum current and be completed before a quarter of a period, the rate of change of current would naturally be much greater than if the current were allowed to follow the ordinary wave. In order to avoid this danger, it is advisable not to go too far in reducing the time required for completing the break of current; it should in no case be less than a quarter of a period.

Dr. Garrard. Dr. C. C. GARRARD: I would like first to enter a plea for simplicity in methods of electrical protection. The paper clearly shows that the systems of control proposed are becoming very complicated. For each cable we have one or more auxiliary pilot cable; presently, I doubt not, we shall be confronted with the proposition to use further cables to protect these auxiliary cables and so on. Now, this is not a fantastic idea, as the keeping in proper condition of the pilot cables is very important. These are liable to be damaged by mechanical disturbance, atmospheric effects, etc., almost as much as the main cable. In fact, I think it may be asserted that the majority of breakdowns of cables come from immediate causes exterior to the cable, which causes would be nearly as likely to damage the pilot cable as the main cable. There can be no doubt that the great disadvantage of the Merz-Price system is the pilot. Unfortunately, in certain circumstances, the pilot wire is necessary and it then has to be used. But a system which may be designated the Merz-Price system run mad, with a maze of pilot wires everywhere, is to be strongly deprecated. The most useful sphere of application of the Merz-Price system is the

interconnector, or any cable in which power may flow properly in either direction. The use of interconnector cable is, however, not always an advantage from the point of view of cost, as not only must the actual length of cables be taken into account, but also the cost of laying, obtaining way leaves, etc. Another point to bear in mind, and this applies equally to duplicate feeders, is whether the interconnector or duplicate feeder has always to be connected up to the bus-bars for any reason, say to prevent excessive drop of potential, or whether it is to be regarded as a pure standby in case of breakdown of the ordinary cable. A cable which is always kept connected to the bus-bars cannot, I consider, be regarded as a duplicate one. Duplicate feeders, for example, should only be used one at a time, say on alternate days. In many cases, also, the interconnector is used in the same manner, that is to say, one substation is connected to another so as to ensure an alternative supply should the feeder to the one break down. For ordinary working, however, the interconnector cable remains disconnected from the bars. This may modify the system of control necessary to be adopted. It must not be forgotten that the Merz-Price gear is not sufficient for the entire protection of a generating and distribution system. It is true it protects the cables against short circuits or grounds, but it affords no protection against overloads or switchboard faults, or a short circuit on the bus-bars. For generator protection all it guards against is the very rare occurrence of a breakdown of insulation of the machine to earth. I am of opinion that reverse-power relays fitted with a time lag form a better protection for generators. Dr. Garrard.

For ordinary feeders, I am also of opinion that it is not worth while to add the complication of Merz-Price gear. These feeders must be protected against overload in any case, and the Merz-Price gear would have to be installed in addition to the time-limit overload outgoing relays. The addition of reverse relays at the far end of the feeder secures sufficient protection. If the feeders be run in duplicate with both always connected, then discriminating arrangements to cut out the faulty feeder and leave the good one connected can be installed without the necessity of pilot wires. Some of these methods are referred to in the paper. Referring now to branch feeders, the authors refer to Fig. 18 as a branch feeder, but this is hardly the case, as the joint constitutes a substation, since there are switches situated there, with, of course, an attendant to look after them. This is rather the case of a substation with two on-going feeders. With the arrangement illustrated in Fig. 17, the authors refer to the special difficulties which have to be got over to ensure that the sum of the three voltages is zero. It seems to me that if the branch represents an important load it would be best to run two cables to the point where they branch. As the two cables would be laid at once, or at any rate pulled through two pipes in the same trench, this would not be a much greater expense and would obviate the likelihood of a fault on the branch entirely shutting down the whole of the main cable. The true use of branch

Dr. Garrard. circuits, however, is to take tappings off a main feeder for customers *en route*. If this be done the probability is there would be more than one, and if several are connected up the difficulties in securing voltage balance of all the branches would be well nigh insurmountable. I am fully in agreement with the authors when they state that the best way in which the Merz-Price system can be applied is the balanced current method. The authors have sufficiently indicated the difficulties of the balanced voltage system. It must be remembered that the control gear is under the charge, to a very large extent, of people who are not skilled electricians. It is not to be expected that such people will make a calculation such as is given in the appendix of the paper in order to find out what any particular setting of the relay may mean. In fact, I take it that this appendix particularly shows that with the balanced voltage system it is impossible to calibrate the relays or tell beforehand at what particular fault current they will operate. This can only be found in practice by actual trial. With the balanced current system, the previous calibration of the relays, etc., should be a much easier matter, as the current transformers act throughout as pure current transformers, that is to say, with equal primary and secondary ampere-turns. I regard this as a matter of some importance, for I think all control gear should be capable of being periodically tested, say in the works test-room, without interrupting the running of the system. With the balanced-voltage system this testing would be very difficult.

Attention is drawn by the authors to the fact that the Merz-Price system allows of a freer lay-out of the cable system. This is undoubtedly true in that it gives us a means of protection of interconnectors and ring mains, but I think that it is possible to carry this feeder lay-out to a dangerous extent. This applies especially when two or more generating stations are connected to a common distribution system. Recent experience has shown that the effect of a breakdown can be very disastrous if backed up by a large amount of generating plant. Now, to a consumer there is no particular advantage to have this supply floating, so to say, between two generating stations. His purpose is served if, when generating, starter No. 1 fails, he can get a supply quickly from station No. 2. Taking the scheme given in Fig. 1 in the paper, I think that for normal running there should be two breaks in the ring main so that substations S5, S1, S2, and S7 are fed from A and the remainder from A1. In the event of A failing, however, the switches which open the ring main could be closed and the entire supply taken from A1 with A disconnected. In other words, while adhering to the advantage of an alternative supply we keep the amount of plant which could feed, say, a fault consisting of a broken-down oil-switch—a fault which, by the way, would not be guarded against by the Merz-Price system—to a minimum. In conclusion, I am of opinion that the Merz-Price system is an excellent one when used in the proper place, but think it wrong to regard it as a universal system of control to the exclusion of all others.

Mr. E. B. WEDMORE: It may be of interest to state that the circulating current system shown in a number of the authors' figures was independently developed by the British Thomson-Houston Company, who have used it successfully and extensively for a number of years. We have also had under consideration the advantages of the circulating-current system as applied to feeder protection, and have developed methods of compensating not only for the pilot-wire drop as illustrated by the authors, but also for capacity current in the pilot wire. As applied to generator and transformer protection, it will be understood that the advantage of the circulating-current system is that the usual series tripping devices of substantial construction could be employed in place of delicate relays, and thus auxiliary supply for tripping purposes is no longer required. It is not unlikely that the same will apply to short feeders, but where sensitive relays may be required the advantages attached to the use of auxiliary supply for tripping purposes could be retained. These advantages are, that the condition of the tripping devices can be readily ascertained by direct test and that plenty of energy is available for causing the switches to trip quickly. I attach great importance to the employment of quick-acting switches for dealing successfully with fault conditions. When an oil-switch trips there are several distinct operations to be completed before the contacts commence to separate, and under severe conditions the arc will not be ruptured immediately on separation of the contacts. Whilst the development of heavy faults when insulation is punctured is commonly described as practically instantaneous on extra-high-tension service, it has to be recognised that this is not a correct description, and if the switchgear can be made to operate in a time which is short as compared with the time taken to burn a hole sufficient to develop a short circuit to its full extent, the fault can be cleared with much less disturbance of the system. Quick-acting switchgear has been employed under conditions where, theoretically, the devices should not have dealt successfully with the fault conditions, and yet, owing to quick operation, the apparatus has been able to clear the faults without disturbance to the system.

Mr. Wedmore.

The problem of dealing successfully with faulty conditions is not simply a question of isolating the faulty section of the system, but an equally important feature is that this isolation should be carried out without the production of disturbances in this system. It is common experience on some systems that heavy faults invariably cause the disconnection of live load in various remote parts of the system. Moreover, it is well recognised that static disturbances are liable to be set up by faults. Having regard to the above considerations, I am of opinion that if the circulating current system, as applied to feeder protection, can be made considerably more sensitive than the systems now employed, as we anticipate, better results will be experienced. The conditions in a system where the demand is concentrated in a small area are likely to be very severe. The effect on the generating plant is greater than where long feeders or where transformers inter-

Mr. Wedmore.

vene. It is in just such a system that the circulating-current system is likely to show material advantages. The authors have referred to certain devices I have developed for dealing with distributing systems which employ duplicate feeders operating in parallel. The arrangements illustrated by them are typical of these devices, but Fig. 27 is incomplete, which accounts for the defects in the arrangement discovered by the authors. My scheme includes the employment of reverse-current relays normally short-circuiting the trip coils at the right-hand end. These relays serve to ensure that only the defective feeder shall be disconnected on a fault. It is not suggested that the system is proof under all conditions, and such a system has yet to be developed, but owing to the extreme rapidity with which the reverse relays employed will operate, I may say that all faults met with hitherto in service have been successfully negotiated by these relays, and whilst some 200 of them are in use on generators and feeders, I have yet to hear of a case where a switch has been opened that should not have been opened by the automatics provided. Some of the first relays of this type are installed on generators at Summer Lane station, where they were subjected to very severe tests before they were put into service.

Messrs. Faye-Hansen & Harlow.

Messrs. K. FAYE-HANSEN and G. HARLOW (*in reply*): Referring to Mr. Hunter's criticism, we would say that besides very extensive shop tests we have certainly had more experience of the actual working of the gear than he seems to be aware of. We had, of course, before starting the development of our gear, and even before deciding to become licencees of the Merz-Price Patents, obtained information regarding the difficulties met with in the first installations in the Newcastle-upon-Tyne system and the first installations in Germany. Regarding the diagram of connections in actual use, several other schemes of connections besides those of Figs. 9, 13, and 17 have been adopted on a commercial scale, though some of the diagrams have been included to show the principles involved and also to show which connections should be adopted under different conditions. Coming now to the system developed by the authors, Mr. Hunter will agree that it is an advantage in case of a break in a pilot wire, that the gear will operate (instead of having the feeder unprotected as in the balanced voltage system), even if a large current is required for such tripping. If, as proposed by the authors, normal full-load current only is required for tripping under the worst possible conditions, the advantage is obvious, since the gear in case of a break of a pilot wire will operate at approximately one-fifth full-load current (with reference to Fig. 24). Mr. Hunter objects to the authors' schemes in Figs. 23 and 24 on the ground that too many parts require balancing. The facts, however, are just the opposite, since experience has shown that the whole system is easier to balance than the balanced voltage system. In a distribution system as on the North-East coast it is, of course, quite satisfactory that a fault current several times larger than the normal full-load current is required for tripping, but on smaller

Messrs. Faye-Hansen & Harlow.

systems this might result in the gear not operating even in the case of a dead fault, should this occur when only a small part of the total generating plant is running. This is also the reason for the discrepancy between the 5 volt-amperes input in the transformers mentioned by Mr. Hunter and the authors' figure of 41 volt-amperes (Table A, column 1), which is calculated on existing apparatus of which hundreds are installed, and not on theoretical apparatus. For a just comparison it is the volt-ampere input at a current corresponding to the fault current required to operate under the least favourable conditions which must be compared, and if this fault current is, for instance, three times the normal full-load current, the input of the series transformers used on the North-East coast system would be 45 volt-amperes compared with 41 volt-amperes in Table A. As pointed out several times in the paper, both series transformers and voltages can be made smaller if the conditions are such that the gear only need operate at fault currents, which are large compared with the normal full-load current. We cannot quite agree with Mr. Hunter that the normal full-load current should be forgotten when designing the protection gear, but we agree that the maximum fault conditions should be kept prominently in mind. The series transformers should be designed to carry this current for as long a time as the protected cable, that is, the primary winding must have a section approximately equal to that of the cable. This can be done without using a large amount of material in the construction of the series transformers and without making them heavy and cumbersome.

Mr. Clothier made some remarks on series transformers having only one primary turn. We agree that the insulation of the primary conductor is easier in this type than in the ordinary series type transformer, but so far as the insulation between secondary turns and also the testing for balancing is concerned, we cannot see any advantage of the single-turn over other series transformers. In case of small systems where the gear is required to trip at small fault currents (say 100 amperes) it is, however, difficult to obtain satisfactory results with a single-turn series transformer. With regard to Mr. Clothier's remarks on balancing, it is possible to test transformers up to many times full-load current independent of type and number of primary turns. We have made a practice of testing the series transformers at approximately 20 times the full-load current. A statement of the volt-amperes input at full load and the straight line characteristic up to 20 to 30 times full-load current does not give any real information regarding the gear, as Mr. Clothier has omitted to state the fault current at which it will operate under the least favourable conditions; this was previously pointed out in reply to Mr. Hunter. Referring to the trouble due to capacity currents Mr. Clothier is of course right that at a given voltage a six-mile cable has such a resistance as to limit the primary short-circuit current. Assuming, however, 1,000 amperes per square inch as normal current density in the cable system, then in an

Messrs. Faye-Hansen & Harlow.

11,000 volt 3-phase system the maximum short-circuit current on a 6-mile feeder is approximately 25 times full-load current. With absolutely straight line characteristic series transformers and unlimited supply at the back of a fault, the capacity current flowing in the pilot wires at short circuit is independent of the length of pilot wire, but proportional to the voltage of the system, so that under these conditions the safety from capacity current is independent of the length of feeder. If, however the series transformer has only a straight-line characteristic up to a certain value, or the power behind the fault is limited, the danger of tripping due to capacity currents increases with the length of the feeder. We would point out, however, that any slight out of balance in the series transformer, which might cause overload tripping on short feeders, would not have any effect on long feeder sections, since the resistance of the pilot wires reduces the secondary current, due to such out of balance.

Mr. Clothier has criticised the relay shown in Fig. 31. In this connection we would say that the masses in the relays are so small compared with those in the switch mechanism, that the reduction in total time for operation, even if the masses are reduced, is negligible, especially as this only can be done by reducing the operating forces. The robustness of the relay would be reduced and the danger of operation due to mechanical vibration increased, if these masses were reduced. We are still under the impression that the additional contact in Fig. 32 has been put in as a result of observation that the first contact is unreliable, due to the exceedingly light armature and the small forces to operate the same. The relay in Fig. 31 could easily be fitted with an auxiliary contact attached to the indicating device, giving it all the alleged advantages for Fig. 32, but the authors consider that the disadvantages introduced entirely outweigh the advantages, which latter really are only imaginary when the first contact is made reliable. Regarding the neutral wire balancing mentioned by Mr. Clothier, this is really a mixture of the balanced voltage and the balanced current system, the secondaries of series transformers having different primary currents being connected in series. Such a connection does not have the main advantages of the balanced current system compared with the balanced voltage system. In the authors' system there are two losses—the losses in the series transformers and in the pilot wires. Both are approximately proportional to the square of the current going through the feeder, and will together only be approximately 5 per cent. of the feeder loss, assuming a 200-ampere feeder. If the feeder loss is 2 per cent. at normal full-load current, the loss in the protective gear would be approximately 0·1 per cent. In case operation at a larger fault current than normal full-load current is satisfactory, the losses will be correspondingly smaller, so that this point certainly is of no importance. We would remark, however, that if the current required to operate under the worst possible conditions need not be less than 3 times the full-load current of the feeder, the input of the series transformers

at normal full-load current would be 14 volt-amperes. This figure is for a 6-mile feeder, and for shorter feeders the figures will be considerably lower. Messrs. Faye-Hansen & Harlow.

The use of the direct-current trip is alleged to have the advantage that it renders periodical testing easy to carry out. Now, we would point out that this is usually done by operating the relay by hand, thus ignoring any fault which might occur on the relay or relay circuit. We consider it quite as necessary to test the relay as to test the trip coil, and the equivalent to the above test on alternating-current tripping is to operate the trip coil by hand. The system of testing we suggest for Fig. 24 is to open-circuit the pilot wires at any point. If the gear is set to work at 100 per cent. of full-load current under the worst possible conditions, it will then trip if the load current is 20 per cent. of the full-load current.

With most of Mr. Wedmore's remarks we entirely agree. He states, however, that the reason for the authors' criticism of the system shown in Fig. 27 is due to the fact that this figure is incomplete, and he would put in two reverse-current relays to make the gear discriminative. We have not shown these relays, as thereby the question of drop in voltage in case of fault and also the question of shunt transformers comes in. Further, if a fault should occur near the generating end of one feeder, the power in both feeders may reverse if there is synchronous plant running at the substation end. If such reversal of power cannot take place, ordinary reverse-current relays would give the same discriminative protection as the balanced system proposed by him. The protective system shown in Fig. 29, however, would be discriminating under all circumstances. Mr. McKenzie criticises our action in not recommending the Merz-Price gear for use with generators. We might have expressed ourselves more clearly. What we intended to convey was that it should not be used for generators, except in conjunction with other protection, as we certainly think it advisable to protect a generator against loss of field, loss of power, and especially it should be cut out at once in case of failure between different parts of one phase, as otherwise great strain might be put on the rest of the generating plant; and the damage to the generator itself will, of course, be considerably greater if the generator is not cut out until the fault has developed into an earth.

Replying to Mr. Chamen's remark on testing, these are already dealt with in the reply to Mr. Clothier. We have pointed out in the paper that two pilot wires can be used with the balanced voltage system, but due to the large impedance in series this connection has seldom been adopted in practice. We still believe that the balanced current system proposed by us is easier to maintain and keep in order, since resistances are much simpler than relays and batteries. The extra series transformer at each end is only put in to obtain the advantage of using two pilot wires in place of three. We have manufactured balance voltage transformers with air-gaps and balanced current transformers without

Messrs. Faye-Hansen & Harlow.

air-gaps, and have found in practice that the latter are much easier to balance. With reference to Mr. Chamen's remarks on sensitiveness we have stated that, inherently, the balanced current system is more sensitive, using the same relays, etc., but we propose to use this advantage to obtain a simpler and more reliable gear by doing without relays and batteries, and to keep the sensitiveness the same from an operating standpoint. As regards teed feeders generally, and Fig. 26 in particular, as an example of this, the arrangement will operate quite successfully until saturation is reached (just as with the balanced voltage system), and after saturation the out-of-balance must reach approximately 30 volt-amperes to operate the trip coil direct, while only approximately 0·9 volt-ampere out-of-balance is required with the balanced voltage system. Due to the fact that the impedance of other transformers and relays have not to be overcome in the balanced current system (as opposed to the balanced voltage system), this operation can be obtained without the series transformers reaching an excessive size. The protection of transformers having tappings has been referred to. We may say that the necessity for the series transformers having tappings depends on the size of the tappings, and the short-circuit current of the protected transformer. The protection of generators has been dealt with in our reply to Mr. McKenzie on the same subject.

Replying to Mr. Taylor, we would point out that the reason the minimum tripping current should be kept closely in mind, is that the gear must operate when a fault occurs with the minimum generating plant running and with the fault current limited by resistance between neutral and earth. It is desirable to have this minimum operating current as high as possible when the above condition is adhered to, as thereby the size of series transformers and the maximum voltage, etc., are kept down, and it is easier to arrange the design so that overload tripping with maximum fault currents flowing over healthy sections will not occur. With reference to the diagram, Fig. 19, we can assure Mr. Taylor that the proposed fourth transformer will solve the difficulty, and that the gear will operate in case of a short between phases (2) and (3). The secondary voltages of the series transformers in these phases have the same phase-angle between one another as in star-connection (Fig. 13), and the secondary voltages set up by a fault-current between these two phases assist each other to force the operating current through the relays and pilot-wires as in star-connection. We are interested to hear that Mr. Taylor has succeeded in designing a switch to operate in the time and in the manner shown in his diagram, and which can be relied upon to open the circuit in one five-hundredth part of a second without causing dangerous voltage rises. We shall be glad when Mr. Taylor is at liberty to divulge full particulars. Regarding the protection of ring mains without pilot wires by means of a relay opening more quickly the lower the voltage (which would be easy to construct), we regret that Mr. Taylor has not explained his idea more fully, as we are unable to conceive such a system of protection which would be successful for

Messrs. Faye-Hansen & Harlow.

use on ring mains without cutting out any substation in case of a cable fault. Dr. Kloss asks if the higher harmonics affect operation in the connection of Figs. 8 and 9. We would state that in neither of these cases is trouble to be expected, though in the case of Fig. 9 it is theoretically possible. For transformer protection as in Fig. 9 the gear has to be set so that it will not be operated by the no-load current, and the higher harmonics are not likely to be so large as this. We are in agreement with most of Dr. Garrard's remarks, though we think that he does not quite do justice to all the cases in which Merz-Price gear may be used to advantage. With reference to his remarks regarding the setting of relays, this should of course not be left to the station attendant, but be carried out by the manufacturer or to his directions.

MEASUREMENT OF RELATIVE ANGULAR DISPLACEMENT IN SYNCHRONOUS MACHINES.

By W. W. FIRTH, M.Sc.

(*Paper received January* 27, 1911, *read before the* NEWCASTLE LOCAL SECTION *February* 20, 1911.)

When the working conditions of a generator and synchronous motor system are changed by alteration of load or excitation of either machine, a relative mechanical displacement of the rotors takes place, and if the change is sufficiently rapid, there is an oscillation or phase swing about the new position of equilibrium which is quickly damped out by eddy currents and friction.

The magnitude of the steady displacement is governed by the condition that the vector sum of the circuit voltages must be zero, or in other words, that the resultant of the generated voltages of generator and motor is equal to the impedance-drop in the circuit. These voltages depend upon the exciting currents of the machines together with their armature reactions, whilst the impedance drop is proportional to the line current.

To understand the cause of phase displacement, it is necessary to examine in some detail the influence of the armature flux in modifying the effective strength of the magnetic field. Consider a 3-phase generator and motor system, and assume the distribution of pole and armature fluxes to be sinuous in space around the circumference of the armature. The conditions in the generator are represented by Fig. 1 (I.), A, B, and C being the coils of the three phases. Let the current in phase A reach its maximum value when the coil edge is $\theta_G{}^\circ$ of phase from the pole centre, reckoned positive to the right and negative to the left of the centre line. At this instant the currents in phases B and C have reached half their maximum values, and are reversed in direction compared with that in phase A. The corresponding magnetic fields are shown by the curves *a*, *b*, and *c* of Fig. 1 (II.), and their resultant by the curve N_A. The latter is seen to be in phase with curve *a*, that is, the maximum value of the resultant armature flux occurs 90° of phase later than the maximum current in any coil edge; this flux is therefore fixed in magnitude and in position relative to the pole-flux N_P, the phase difference being $(90 + \theta_G)$ degrees.

When any coil edge passes through these magnetic fields, voltages are generated proportional in magnitude to and in the same phase as the fields. These are shown in the vector diagram Fig. 1 (III.), by

V_{GP} and V_{GA}, and the resultant voltage of the armature by V_{GR}. The current I. reaches its maximum value 90° of phase in front of V_{GA} or ϕ_G behind the resultant voltage, ϕ_G being the angle of lag of the current in the generator. The corresponding diagram for the motor is

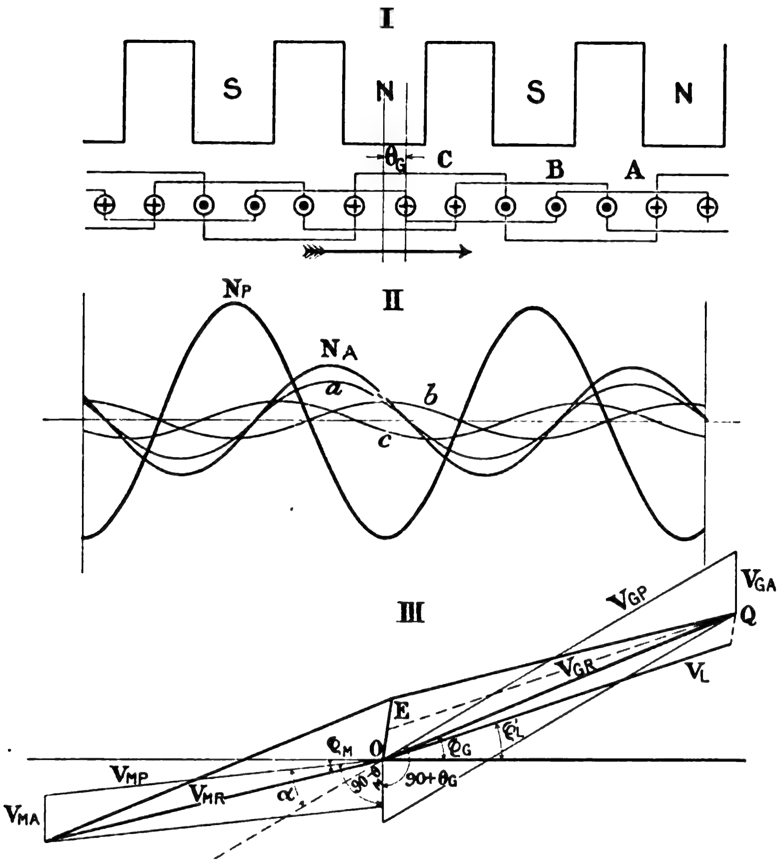


FIG. I.

I.—Poles and armature with phases A B G.
II.—Full diagram when current in phase A reaches its maximum a, b, and c fluxes due to phases; N their resultant; N_2 the pole-flux.
III.—Vector diagram of voltages generated by pole armature and resultant fluxes ϕ_G, ϕ_M, and ϕ_L the angles of lag in generator, motor, and line respectively.

obtained by reversing the current and the armature fluxes in Fig. 1 (I. and II.); the phase difference of pole and armature fields is now $(90 - \theta_M)$ with the armature flux leading, θ_M being the displacement of the coil edge from the pole centre when the current reaches its maximum value. V_{MP}, V_{MA}, and V_{MR} of Fig. 1 (III.) are the voltages

generated by pole, armature, and resultant fields of the motor respectively.

Combining the resultant voltages of generator and motor gives the impedance drop E of the circuit.

If the machines are similar the drop E is equally divided between them, and the line voltage is represented in magnitude and phase position, by V_L drawn through O parallel to the line from the middle point of E to Q.

Phase Displacement shown in Diagram.—When the machines are running in parallel as generators without exchange of current the vector diagram reduces to two vectors, V_{GP} and V_{MP}, equal to one another and in opposition. In this case the corresponding coil edges of the generator and motor pass the pole centres at the same instant. Under load conditions, V_{GP} and V_{MP} swing towards one another, and the coil edges now pass the pole centres at an interval of time represented by the angle α in the vector diagram. This angle, therefore, is the relative mechanical displacement in degrees of phase from no load to full load. The diagram shows that this change of phase position is partly due to the change of impedance drop, but chiefly to the change of the generated voltages by armature reaction. Incidentally, the vector diagram of Fig. 1 shows that even when the power factor in the generator is unity, armature reaction has a weakening effect on the main field; in fact, that the angle of lead must be considerable before the action becomes strengthening, that is before V_{GR} is greater than V_{GP}. It shows also that in the motor the armature field weakens the main field when ϕ_M is zero and only strengthens it when the lag is fairly large. Stated generally, we may say that a lagging current in the line always has a demagnetising action in the generator, and a leading current a demagnetising one in the motor; further, that to produce a magnetising action in the generator or motor, the line lead or lag respectively must exceed a certain value which depends upon the magnitude of the line current.

To test the truth of these conclusions, exploring coils were wound round the yokes of the two machines and connected in turn to a ballistic galvanometer so that any change of flux in the machine under test could be observed. When running under steady conditions the synchronising switches were opened and the direction of the kick of the galvanometer noted; it was found that the exploring coil on the 3-phase generator field gave no magnetic kick when the current lead in the line, calculated from the wattmeter readings, was 28°. For greater values it was magnetising, and for smaller ones demagnetising. Similarly when the galvanometer was connected to the exploring coil on the motor, there was no effect when the lag in the line was 10·5°; for greater values it was magnetising, and for smaller ones demagnetising. The same results were obtained whether the exploring coils were around the yokes or immediately behind the pole-shoes.

Description of Apparatus for observing Phase Displacement.—The machines on which the tests were made are two similar 5-k.w.

Westinghouse 4-pole separately excited converters (direct-current 100 volts) with connections for both single- and 3-phase working. The generator was driven by a direct-coupled direct-current motor, and the second machine when running as a synchronous motor was loaded by a direct-current direct-coupled generator, and when running as converter, by rheostats. The four machines are in line, with the synchronous machines in the centre. Fig. 2 shows diagrammatically the apparatus used for observing or recording phase displacement.

Fixed on the half coupling on the motor shaft is a sheet-iron ring R carrying a pin-hole H. On the end of the shaft of the generator is

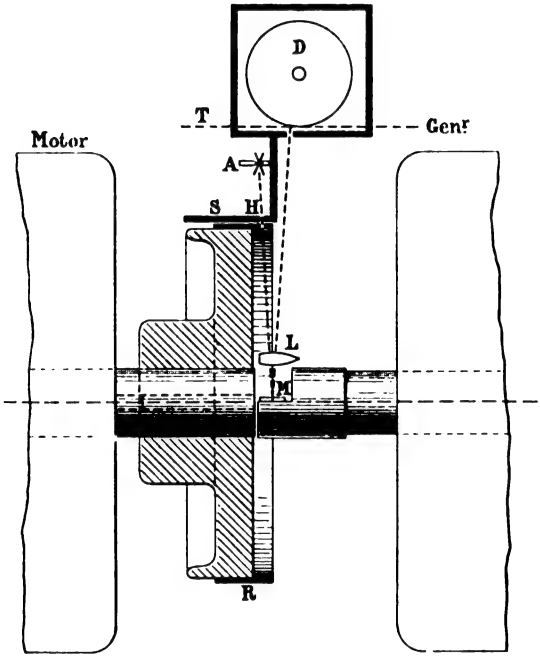


FIG. 2.—Apparatus for Recording Phase Swing.

fixed a small mirror M with its reflecting surface in the axes of rotation; S is a fixed shield with another pin-hole on it opposite to that in the ring. The light from an arc A passes through the two holes in line once per revolution of the motor, and strikes the mirror M if the latter is suitably adjusted with reference to the synchronous position of running. Thence it passes through the fixed lens L to the tracing-screen T, or alternatively to the drum D, which carries the recording sensitive paper. When relative motion of the armatures takes place, its amount is measured by the change of position of the spot of light on

the screen or drum. The spot of light is intermittent, which, when phase swing occurs, gives rise to a series of dots on the sensitive paper.

The apparatus was calibrated with the machines standing and the pin-holes in line. It was found that equal angles of turning of the generator armature gave equal displacements on the screen of the spot of light, the errors of refraction of the lens almost exactly compensating for lack of curvature of the screen.

Observations of the steady displacement with change of load and with change of excitation are plotted in Figs. 3, 4, and 5. Fig. 3 gives the curves for change of load with constant excitation in both machines, for single- and for 3-phase motors and converters. The displacements at two constant speeds are given for each type, from

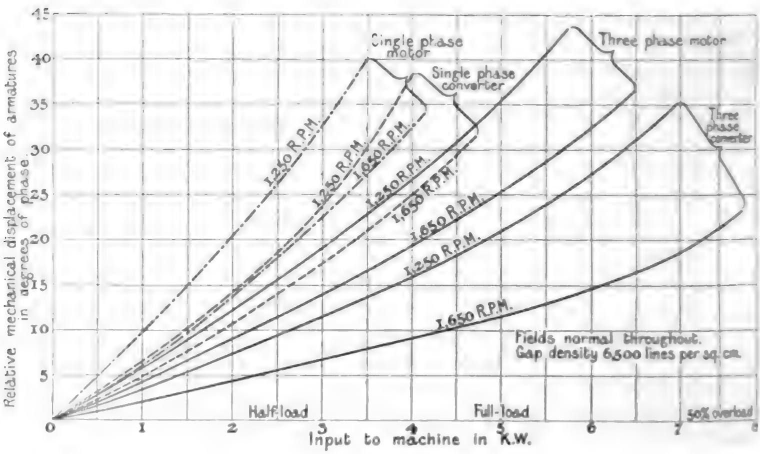


FIG. 3.—Phase Displacement with Change of Load in Single- and 3-phase Synchronous Motors and Converters.

which it will be noticed that the displacement decreases with increase of speed for any given load; that it is much less in 3- than single-phase machines and less again for converters than for synchronous motors. The latter might be predicted from the fact that in converters armature reaction is much smaller than in synchronous motors.

Figs. 4 and 5 show displacements for constant line loads with change of excitation of the motor or converter. The curves are plotted to abscissæ of flux density in the gap measured by the bismuth spiral method, with the machines standing. The generator excitation was maintained constant at a medium value of 6,350 lines per square centimetre.

The displacements are plotted from the point at which the fields of generator and motor were of equal value.

In nearly every case of Figs. 4 and 5 the field of the motor or converter was reduced until the machine broke step. The 3-phase

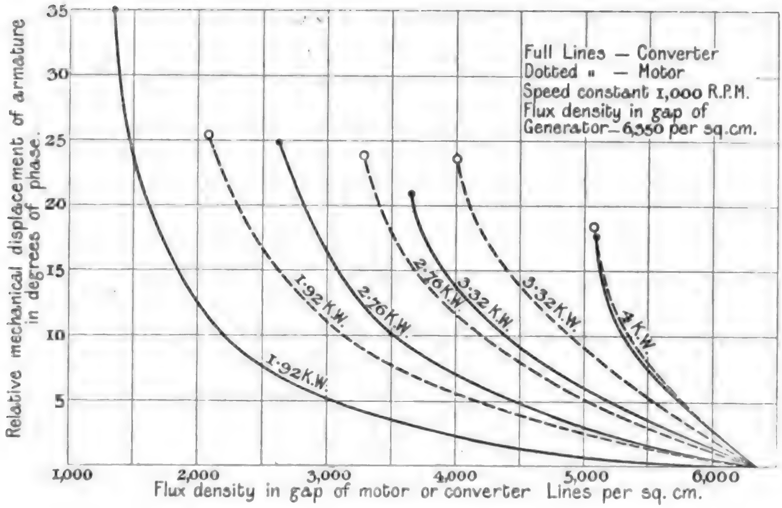


FIG. 4.—Phase Displacement with Change of Excitation in Single-phase Motor and Converter.

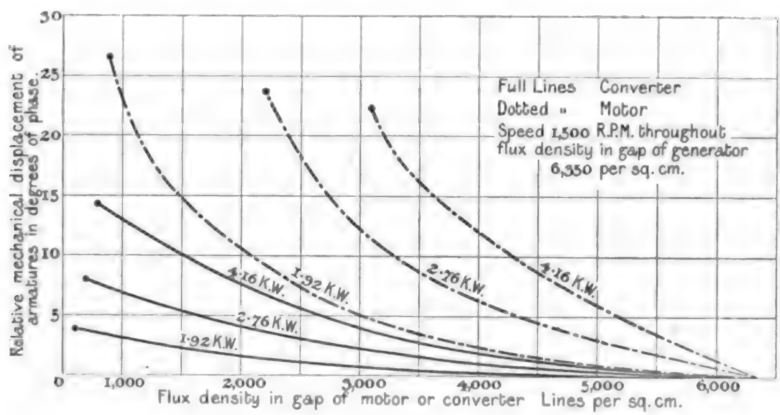


FIG. 5.—Phase Displacement with Change of Excitation on 3-phase Synchronous Motor and Converter.

converter was, however, a striking exception, the machine continued to run on load even when the field circuit was opened. With a

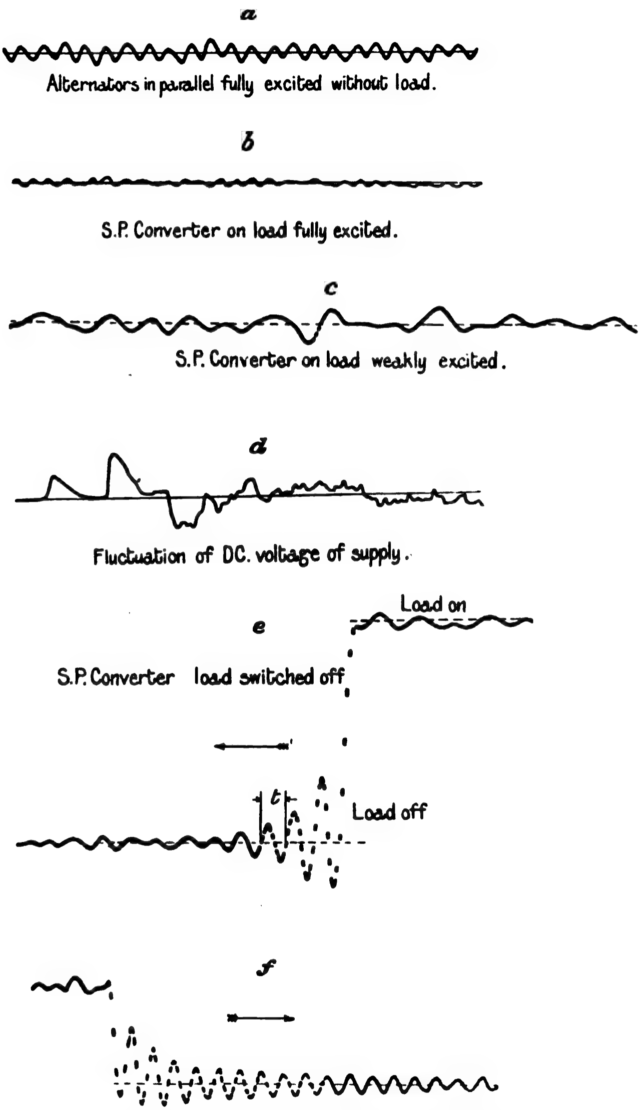


FIG. 6.—Photograph of Phase Displacement and Swing.

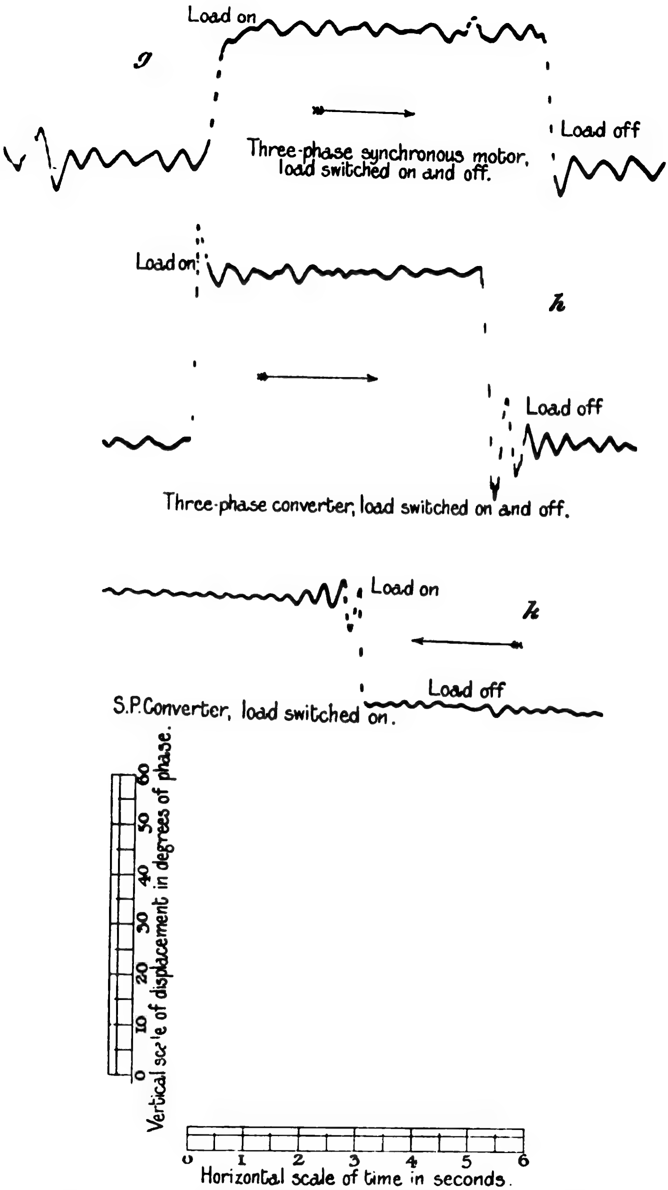


FIG. 6.—Photograph of Phase Displacement and Swing.

reversed field current of about one-fifth the normal value the converter slipped half a cycle and remained in synchronism. It was found impossible to force the machine out of step by any alteration of its excitation. Such a result is possible only in a converter, where the necessary magnetic pull of the lines on the armature conductors is small, viz., that to supply the friction and iron losses of the machine.

Though armature reaction and residual magnetism both play some part in this action, it is probably almost entirely due to the former. When the converter field is weak there is a heavy lagging current which magnetises the main magnetic circuit to a sufficient extent to provide the driving torque of the armature.

The exploring coil and ballistic galvanometer method previously mentioned proved that the main field was strongly magnetised by the armature when the field current was zero.

Fig. 6 is a reproduction of a series of photographs taken with the apparatus. *a*, *b*, and *c* show the phase swinging caused by fluctuation of the supply voltage driving the direct-current motor; this fluctuation is shown in curve *a* and has a maximum value of 10 volts or 2 per cent. of the supply voltage; *g* and *h* show the displacement and swing in 3-phase motor and converter respectively, when the load is thrown on and off. A marked contrast, due to the differing armature reaction, will be noted in the two types of machine. In the motor the influence of eddy currents set up by the moving armature flux during displacement, when load is switched on, is shown by a time retardation of the maximum displacement, which is entirely absent in the converter. The contrast is again seen when the load is switched off, the phase swing of the converter being considerably greater than that of the motor.

The natural period of swing of the synchronous system may be observed in most of the photographs, though it is disturbed in places by the irregular impulses coming through the direct-current motor from the supply.

S. P. Thompson* gives the periodic time of oscillation of a generator and synchronous motor as $T = 25{\cdot}6 \frac{n}{E} \sqrt{LI}$, where n is the speed of the machines in revs. per second, E the generated voltage, I the moment of inertia of the moving parts of the motor, and L the coefficient of self-induction of the two armatures and line.

The natural period measured on the photographs varies from 0·32 second to 0·457 second; it depends upon the excitation and load of the machines. Taking the single-phase example represented by Fig. 5, where—

$$T = 0{\cdot}457, \quad I = 7{\cdot}3 \text{ ft. 2 lbs.}, \quad E = 54, \quad n = 25,$$

we find—

$$L = 0{\cdot}204 \times 10^{-3}, \text{ or per armature } L = 0{\cdot}102 \times 10^{-3} \text{ henries.}$$

* "Dynamo Electric Machinery," vol. 3, p. 526.

The value of L obtained from the mean impedance measured when standing with the armature in various positions and the field excited was 10^{-3} henries.

The great difference between these results seems to indicate that the voltage drop in alternators is almost entirely due to demagnetising armature reaction, the true or leakage inductance drop being practically negligible.

Discussion before the Newcastle Local Section.

Professor W. M THORNTON: Mr. Firth is to be congratulated upon doing a piece of work which has been wanted for a long time. It has been talked of for about eight years, but has not been accomplished until now. I have tried the same thing myself, using a synchronous motor and observing the displacement through a hole in a rotating disc. Mr. Firth has approached the problem in a new way and carried it to a complete solution. It is difficult to realise the amount of relative movement which takes place between machines which are running synchronously When Neptune Bank station was started it was curious to notice the tops of oscillograph curves rippling due to phase swing, the harmonics running up and down the sides of the curves. Since there may be some doubt as to the exact definition of phase swing I might explain that it is a mechanical swing controlled by the elastic nature of the magnetic lines of force, voltage and current remaining strictly in phase in both machines, the latter varying during the swing in time with the movement. When there are very large currents in

Professor Thornton.

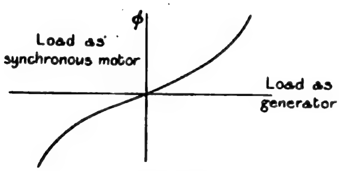


FIG. A.

the armature or large ampere-turns in the poles there is a great sideways displacement of the magnetic field. From Fig. 3, looking at the left-hand side, it will be noticed that the curves go in pairs. Take a simple case with a 6-k.w. 3-phase converter at the higher speed. There is 15 degrees phase displacement between the two machines; this can be looked upon as approximately 7·5 degrees for one machine in one direction and an equal amount for the other machine in the opposite direction, since the machines are exactly alike. There are two problems to investigate—the shift of the load and the shift of field strength. Mr. Leake suggested plotting phase displacement against total load. Mr. Firth's curves (Fig. 3) give the right-hand side, and it

Professor Thornton.

will be noted that these curves do not extend so far as Mr. Leake suggested; at least the working range of these experimental machines does not go so far. One of the principal points brought out by the paper is the change of the actual magnetic centre-line. Hitherto it has been commonly assumed that the maximum voltage is reached when the edge of the coil is in the geometrical centre of the field, but it must not be forgotten that the magnetic centre-line actually moves, due to the bending of the lines on account of the load current. The maximum voltage in a generator is thus reached somewhat later than is commonly assumed. In the usual theory of the armature reaction in alternators it is generally assumed that the demagnetising ampere-turns are proportional to $\sin\phi$, but I would suggest altering this to $\sin(\phi + \alpha)$, α being the angle through which the magnetic centre moves. We thus have for the ratio of the actual back ampere-turns to the calculated ampere-turns $\sin(\phi + \alpha)/\sin\phi$. Take ϕ as 30 degrees and α as 15 degrees, the ratio is then $\sin 45^\circ/\sin 30^\circ = 0{\cdot}707/0{\cdot}5 - 1{\cdot}41$. It would thus appear that in these experimental machines at least there is 40 per cent. more armature reaction than is given by the generally accepted theory.

In the Potier and Fisher-Hinnen methods of predetermining alternator characteristics the voltage is measured with ϕ nearly equal to 90 degrees, but it is questionable whether it is correct to do this, as the values arrived at are probably in error, due to the phase displacement. This might be one reason why the predetermined characteristics of large machines generally require some adjustment later. The throw which is actually obtained as a result of a change of magnetism in the search coil shows that there is a marked effect due to the armature current, although the current and volts are in phase. It may be that the neglect of the field shown by the exploring coils in the paper to exist when ϕ is zero, is counteracted by the neglect of the effect of displacement of the field sideways, for if the effect of this mechanical displacement of the armature coils is neglected the field ampere-turns as calculated will be too small, whereas if they are estimated from a full-load current test on a power-factor zero they are probably too high. In Fig. 3 we see that the alteration in phase displacement is much less on 3-phase machines than on single-phase machines for a given alteration in speed or frequency. The fact that with an increase in frequency a smaller phase movement is obtained is rather opposed to what would be expected. It is generally reckoned that the torque is better with a low- than a high-frequency machine. Figs. 4 and 5 are very interesting as showing the difference there is between single- and 3-phase machines. Take the case of flux density of 1,500 in the two cases; for the single-phase machine there is nearly 24 degrees phase displacement for 1·92 k.w. and in the 3-phase machine there is slightly less than $2\frac{1}{2}$ degrees—that is, nearly nine times the phase displacement; the lines of force in the single-phase machine are bent on the average nine times more for a given load.

Mr. Maccall.

Mr. W. T. MACCALL: I should like to ask Mr. Firth one or two

questions, particularly with regard to Figs. 4 and 5. If I rightly understand, what is plotted here is change of relative mechanical displacement of armature: I think the curves would have been more interesting if they had been plotted to give total displacement of armature, *i.e.*, starting with the motor or converter on no-load, loading it to the required amount, and then weakening the field at constant load. The reason why this would be preferable is that it would enable us to obtain some idea of the conditions under which a synchronous motor or converter will fall out of step, and possibly to predict which of two machines would keep in step longer as the conditions became more onerous. The curves that I have suggested can be obtained approximately by combining Fig. 3 with Figs. 4 and 5, but only approximately because the speeds are different in the two cases, so that if Mr. Firth could let us have the figures it would add to the interest of the paper. I have worked them out approximately for the case of the 3-phase motor, and find that the total relative mechanical displacement when break of step occurs is 36¼°, 38¼°, and 45½° respectively for the three loads of 1·72 k.w., 2·76 k.w., and 4·16 k.w., so that under light load break-of-step occurs with less relative displacement than under heavy load, instead of the contrary result which Fig. 5 appears to show as now plotted. The reason for this apparent anomaly is, of course, that the field has been very much more weakened in the light load case before the break-of-step occurs. In these same figures the flux density plotted is not the actual flux density, but the value which the flux density would have but for armature reaction: to obtain fully the conditions of falling-out-of-step it would be necessary to estimate or measure the actual flux density at, or near, break-of-step conditions. I either misunderstood or do not quite agree with Dr. Thornton's remark regarding the effect on the field of a current of unity power factor. It is true that the usual text-book statement is that such a current produces only distortion of the field with no change of strength, but the application of any of the graphical methods of dealing with armature reaction—Behrend's, Potiers, etc.—shows that the field is weakened as Mr. Firth has experimentally verified. Mr. Maccall.

Mr. W. W. FIRTH (*in reply*): With regard to Mr. Maccall's suggestion to measure total displacement from condition of no-load and equal excitation of the motor and generator is an excellent one, but unfortunately the range of the apparatus would not permit such a large displacement to be measured directly. The method he has adopted of combining Figs. 3 and 5 to obtain the total displacement at break of synchronism would be quite satisfactory if a correction were made for speed in Fig. 3. As Dr. Thornton points out, the ampere-turns of armature reaction are not simply proportional to sin ϕ as is assumed in calculations, but are larger than the value owing to the shift of the magnetic centre-line as load is put on. Potier's method, however, is not open to this objection as Fig. 1, III. shows; the triangle formed by V_{GP}, V_{GA}, and V_{GR} has its sides proportional to the pole ampere-turns, the armature ampere-turns, and the resultant ampere-turns Mr. Firth.

Mr. Firth. respectively, aud the angle between V_{GA} and V_{GR} is $90 + \phi_G$. Thus if the pole and armature ampere-turns are known the effective ampere-turns at any power factor cos ϕ_3 are determinate. The increase of displacement with decrease of speed for a given load shown in Fig. 3 is what might be expected from theoretical considerations; a higher speed is accompanied by a higher voltage in both machines, and, in general, a smaller current (since the power is constant), consequently armature reaction, and therefore displacement, decreases with increased speed.

THE BENKÖ PRIMARY BATTERY AND ITS APPLICATIONS.

By W. R. COOPER, M.A., B.SC., Member.

(*Paper received December* 30, 1910; *received in final form March* 8, 1911.)

At first sight it may seem strange to contribute a paper to this Institution upon a form of primary cell using a bichromate solution. In the early days of the electrical industry such a proceeding was quite usual, but the day when the primary battery using zinc was regarded as a possible competitor with the dynamo has long since passed. Nevertheless, the primary cell should have been rendered more perfect than has been the case; notwithstanding the many years that have elapsed, it has never been so far developed as to give electrical energy conveniently and at a reasonable cost, except when the currents required are very small. Those who have attempted to obtain a constant current of, say, 10 amperes from primary batteries will appreciate the truth of this statement.

Although industrial power from primary batteries consuming zinc is not a commercial proposition, the fact remains that if such a battery could be made to give an output approaching that of the lead accumulator, at a constant E.M.F. and without inconvenience, it would be warmly welcomed, even though the cost of energy were high compared with that of energy from public mains. From force of habit we have come to regard such a result as unattainable, and being myself in this frame of mind I looked upon the Benkö cell, when it was first placed in my hands, with much suspicion. I even went so far as to say that the claims were much too rosy to have any probability of truth; but careful investigation has shown that I was very far mistaken, and thus I feel the results to be of sufficient interest to bring before the Institution.

Principle of the Benkö Cell.—The cell is due to the Hungarian engineer Stephan Benkö, and depends essentially on the idea that if the layer of electrolyte on the positive plate (that is, electro-negative element) is removed as fast as polarisation sets in, the E.M.F. will be maintained constant. The means usually adopted for removing polarisation, which is responsible for most of the trouble in primary cells, are rarely quite effective; and the ineffectiveness of the means becomes more and more evident as the solution becomes exhausted through the action of the cell. The user would not object so much to polarisation in itself if it would remain sensibly constant, but this is seldom the case. The

remedy adopted by Benkö is to use a carbon electrode sufficiently porous to allow the electrolyte to flow through it, thus continually providing a fresh supply to the surface that is tending to polarise. By so doing not only is very effective polarisation obtained (depending, of course, upon the depolarising qualities of the solution and its rate of flow), but for a given current the polarisation remains quite constant provided the cell is not overloaded.

The method of putting this idea into practice will be understood most readily by a description of the cell as at present made.

Description of the Cell.—For the sake of clearness the construction is indicated first diagramatically in Fig. 1. Here the carbon is shown at C,

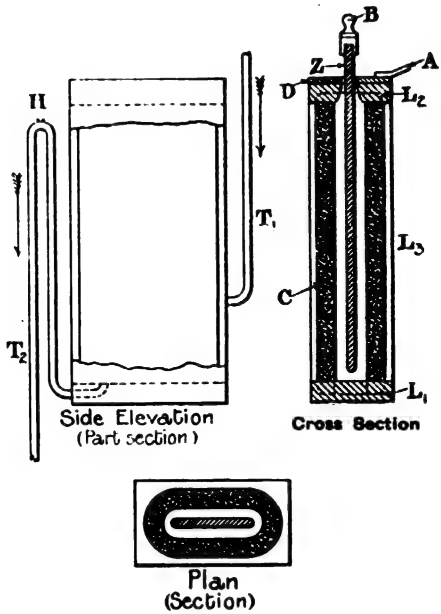


FIG. 1.—Diagram of Benkö Cell.

and this is best described as a flattened cylinder open at both ends. The hard surface of this carbon, as received from the carbon makers, is removed by scratch-brushing so as to leave it easily porous. The carbon is then provided with a lead cap, L_1, at the bottom, and a lead ring L_2 at the top, thus providing a vessel open only at the top. To obtain perfect contact between the carbon and the lead, the latter is put on under pressure by the simple expedient of holding the carbon in a suitable iron holder and dipping it to a depth of 2 metres in a bath of molten lead. Under this pressure the lead penetrates thoroughly into the pores of the carbon and consequently an exceedingly good contact is obtained, the process taking a quarter to half an hour accord-

ing to the thickness of the carbon. The iron holder is provided with formers so that sufficient metal is taken up to form the cap and ring complete in this one operation.

A lead shell, L_3, of sheet lead 1 mm. to 1½ mm. in thickness is then fitted round the carbon, leaving a small space between the carbon and the shell, and is jointed autogenously to the lead cap at the bottom and the lead ring at the top, so as to form a chamber all round the carbon. We thus have two chambers, one inside the carbon and one outside.

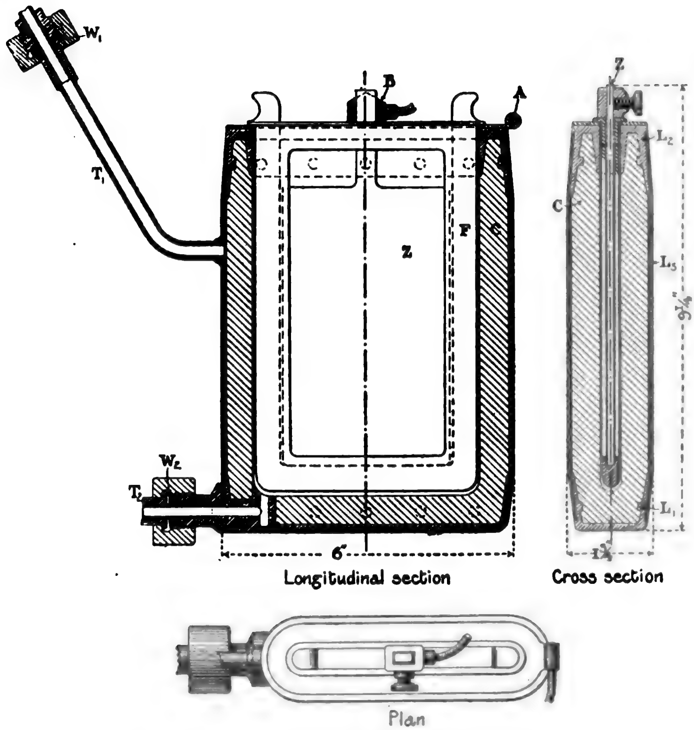


FIG. 2.—Single Benkö Cell (Standard Type).

The outer chamber is provided with a tube, T_1; and a second tube, T_2, is fitted to the lead base and is carried through to the inner chamber. This latter tube is carried up and bent over, and there is a small hole, H, at the top of the bend. Finally a copper plate, D, corresponding with the lead ring, is soldered on to the lead, and forms one terminal, A, of the cell.* The zinc, Z, is inserted into the inner chamber and carries the second terminal, B. When in action the electrolyte is delivered by

* In later designs this copper plate has been abandoned, the terminal being jointed direct to the lead ring.

the lead tube, T_1, into the outer chamber, whence it percolates through the carbon to the zinc; it then flows off through the lead tube, T_2, the form of which maintains the level constant within the carbon. As there is a hole at H, syphoning does not occur, though this may be made to take place in cells so constructed by closing the hole with a finger for a few minutes. This is often convenient when it is desired to empty the cell. It will be noticed that the current is carried away from the carbon at both top and bottom, and owing to this form of construction, and to the excellent contact between the carbon and the lead, very much heavier currents can be taken than is possible with the usual form of joint.

A working drawing of what I will term the "Type A" cell is reproduced in Fig. 2, in which the lettering of Fig. 1 is retained as far as possible. It will be noticed that the space provided between the carbon and the lead shell is very small, only ½ mm. The lead,

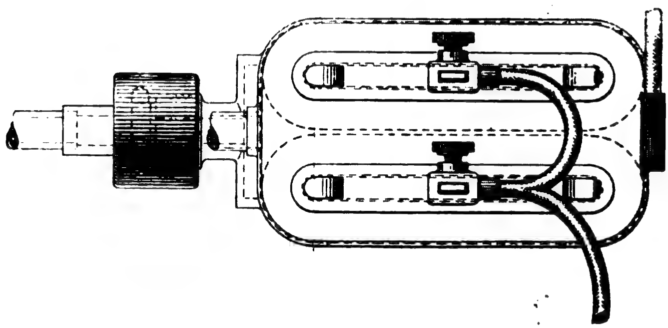


FIG. 4.—Plan of Double Cell.

however, gives somewhat under the pressure of the electrolyte and for that reason it is supported by a wood casing (not shown). The zinc plate is carried in an ebonite frame F. The tubes T_1, T_2, are provided with unions and rubber washers, W_1, W_2, for coupling to other tubes as may be found necessary. (The tube T_2 is not shown carried up.)

Fig. 3 is a view of a single cell with casing, being one of those which were tested. It differs in some small details from the cell shown in Fig. 2.

The carbons at present are not made larger than is shown in Fig. 2, but if larger cells are required this is effected by fitting two or more carbons into one shell. These are thus permanently connected in parallel, and the zincs are correspondingly coupled together. Thus the flow of electrolyte to such a compound cell is regulated by a single tube and the disadvantages of attempting to run separate cells in parallel are avoided. Fig. 4 shows a double cell of this kind. Particulars of single and multiple cells are given in Table I.

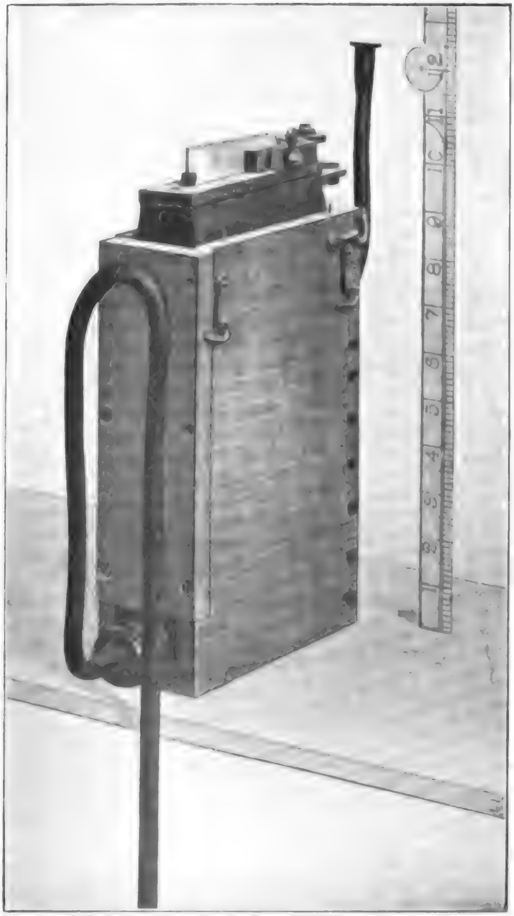


FIG. 3.—View of a Single Benkö Cell used in Tests.

The arrangement adopted for a battery is shown in Fig. 5, which illustrates a standard 7-cell battery, and is reproduced to scale from working drawings. The electrolyte is contained in a lead-lined tank A, from which it flows (due to its own head) down the lead pipe B, through the cock C to the pipe D. The latter branches into a common supply pipe from which each of the cells F is supplied by a tube E, the junctions being by ebonite unions and rubber washers, as already described. Similarly the waste from each cell is carried into a common waste pipe L (by branch tube K), from which an inverted U pipe, G, is taken to maintain the level in the cells, and this discharges into the lower tank H. By means of the cock J the common waste pipe can be opened to this tank so that the cells can be drained, assuming that the supply of electrolyte has been cut off.

TABLE I.

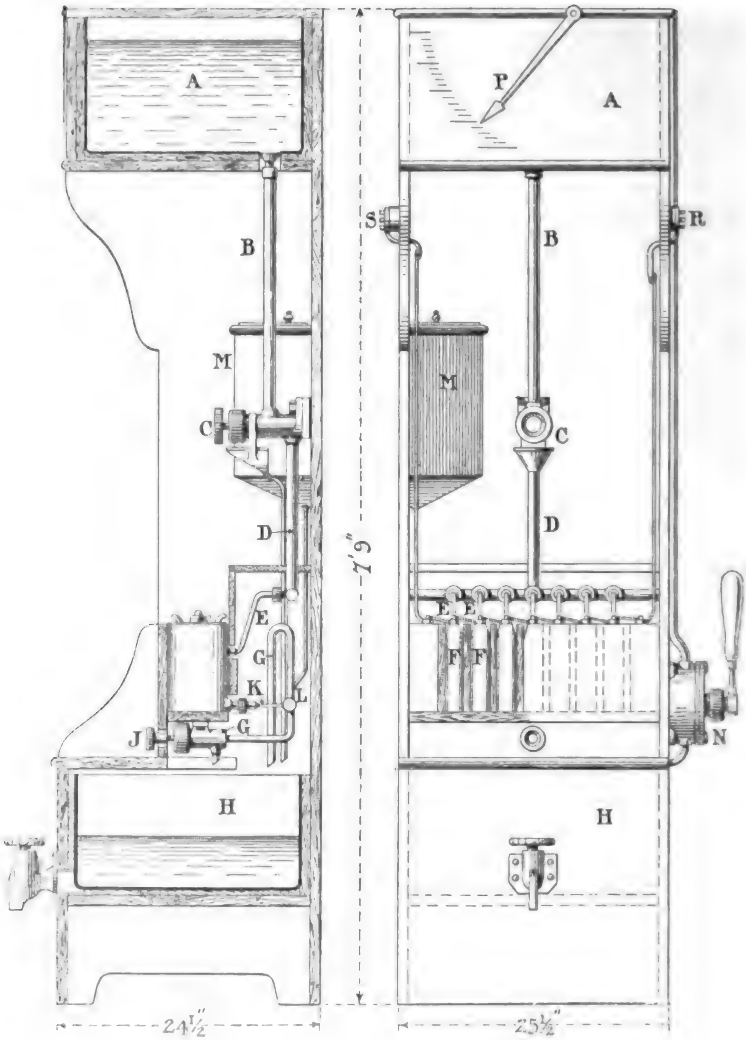
Particulars of Cells (New Design).

	Width.	Length.	Height.	Weight (including Zinc).	Maximum Current with "L" Solution. (Continuously.)	Watts.
	Inches.	Inches.	Inches.	Lbs.	Amperes.	
Single cell ...	$1\frac{3}{4}$	$6\frac{1}{4}$	$9\frac{1}{4}$	8·8	17·5	26·25
Double cell ...	$3\frac{1}{2}$	$6\frac{1}{4}$	$9\frac{1}{4}$	16·5	35·0	52·50
Triple cell ...	$5\frac{1}{4}$	$6\frac{1}{4}$	$9\frac{1}{4}$	26·8	52·5	78·75
Quadruple cell	9	$6\frac{1}{4}$	$9\frac{1}{4}$	36·3	70·0	105·00

Note.—The sizes given include terminals, but exclude pipe connections. The current given is for a voltage of 1·5 volts per cell. E.M.F., 2·0 volts.

When the supply of electrolyte is cut off for the night it is still possible to take sufficient current for two to three lamps. For this purpose, water, contained in the tank M, is allowed to flow into the common waste-pipe L and finds its way into the inner compartments of the cells (the electrolyte having been previously discharged); diffusion then takes place through the carbon. When normal working is resumed the dilute electrolyte so formed is run out. The waste tank is provided with a cock through which the spent electrolyte can be discharged; or if the electrolyte has been only so far used as to be good for further action it can be returned to the top tank by means of the pump N, the level in this tank being indicated by a pointer,

P, actuated by a float. The cells are separated from each other by insulating partitions; they are all connected in series, and the main



Cross Section

Front Elevation

FIG. 5.—Standard 7-cell Battery.

leads are brought up on either side of the stand to terminals R, S.
It will be seen that the arrangement is compact, the width across

the front of the stand being only 25½ in. and the depth from front to back being 24½ in. In order to give the necessary head the overall height is 7 ft. 9 in.* Air pressure might, of course, be used instead of a gravity feed; this would give greater compactness and might be preferable under certain conditions. But even with the arrangement shown, for a battery giving a minimum working pressure of 10·5 volts and a power up to about 260 watts continuously, the space required must be regarded as small.

Tests.

In what follows the results of numerous tests are given on Type A cells, which were very similar to, but not identical with, the new type just described. I would point out that the following figures are only the result of my personal experience and do not necessarily imply that still better results are unobtainable; I do not doubt, however, that any one with a proper knowledge of the battery will be able to obtain results such as those here given. It should also be pointed out that the cells with which I worked must be described as "experimental," by which is meant that they were not manufactured in quantities, and consequently were probably not so good as such cells would be when produced on a large scale and subjected to the standardising effect of ordinary manufacture.

Constancy of E.M.F. and Current.—With a given flow of electrolyte an extremely constant current can be maintained up to a certain limit. This limit depends largely, of course, upon the composition of the electrolyte. Various electrolytes may be used, and in the case of bichromate solutions Benkö recommends the following formulæ:—

Electrolyte "L" for Electric Light, Electrolysis, Etc.

Water	1 litre ...	35 fluid oz.	L.
Sodium bichromate ...	60 grammes	2·1 oz. ...	
Sulphuric acid (concentrated), sp. gr. 1·84	120 c.c. ...	4·2 fluid ...	

Electrolyte "P" for Heavy Currents.

Water	1 litre ...	35 fluid oz.	P.
Sodium bichromate ...	100 grammes	3·5 oz. ...	
Sulphuric acid (concentrated), sp. gr. 1·84 ...	150 c.c. ...	5·25 fluid oz.	

* In later batteries this height has been considerably reduced. See also footnote on p. 760.

Electrolyte "T" for Telegraphic Work.

Water	1 litre ...	35 fluid oz.	T.
Sodium bichromate ...	5 grammes	1·75 oz. ...	
Sulphuric acid (concentrated), sp. gr. 1·84 ...	2·6 c.c. ...	0·88 fluid oz.	

The usual commercial qualities are used, but only clear solution should be taken, because the cell acts as a filter and would become clogged. Potassium bichromate should not be used as it tends to deposit double sulphate crystals when decomposed, and these block up the pores of the carbon. The E.M.F. with these solutions is 2·0 volts, rising sometimes to 2·05 volts.

The currents obtainable continuously with the first two solutions in terms of the area of the zinc (taking both sides into the measurement) may be taken as follows :—

	Per Square Decimetre.	Per Square Foot.
Solution L	6 amperes	56 amperes
Solution P	10 "	93 "

These values, however, may be taken as the limit obtainable with a high rate of flow. When the flow is restricted to ¼ litre per cell the current falls to a lower value (at least with the cells that I have used); thus for solution L it becomes reduced to, say, 30 amperes per square foot if the potential difference is not allowed to fall below 1·5 volts per cell. It is advisable to maintain this pressure limit, because if the potential difference falls below this value for a considerable time the cell appears to be unable to maintain its E.M.F., which may then fall gradually to a low value. This is undesirable, as the pores of the carbon apparently become filled with reduction products and take time to recover (and these products have to be washed out by fresh electrolyte or water).

From the nature of the cell it follows almost as a matter of course that constant currents must be obtainable because the condition of the cell remains unchanged so long as the rate of flow is maintained constant and the internal resistance is fixed. The discharge curve given in Fig. 10 is a confirmation of this view, if such is needed.

Local Action.—With an acid electrolyte there must always be a certain amount of local action, and this can be measured. In the

present case, however, it is impossible to give any definite figures for this loss in a general way because it varies with the flow of electrolyte and with the current taken from the cell (owing to the fact that this alters the composition of the electrolyte) and with the state of the zinc. In a number of experiments on zinc consumption I found that from about one-fifth of the zinc (regarding this as pure zinc) under the best conditions, up to about one-third (with the plates in a poor condition and a rapid flow) appeared to be wasted; but this figure, of course, is in excess of the true local action. It is, however, on open circuit that local action is the most important, and under these conditions the loss in the Benkö cell is much smaller than in other cells of the acid class because the flow can be stopped, and then the amount of electro-

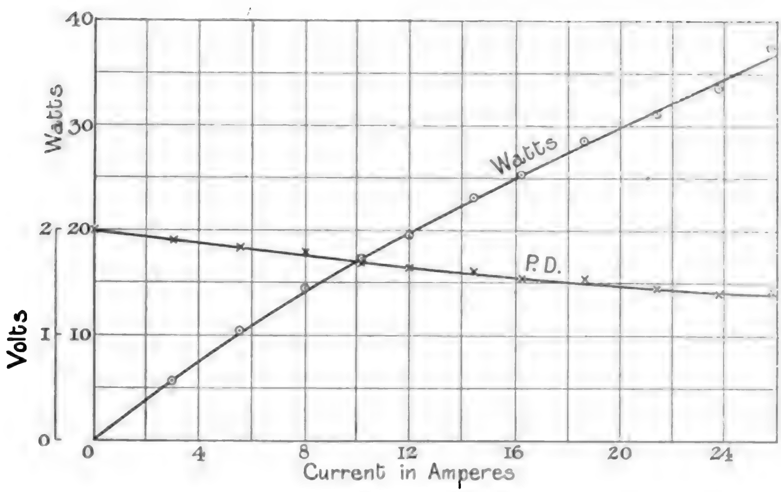


FIG. 6.—Relation of Terminal Volts and Terminal Watts with Amperes.

Type "A" cell. Solution "L."

lyte in contact with the zinc is very small; thus in the A type cell it is less than 200 cub. cms., and this becomes the less effective as regards local action the longer it is in contact with the zinc. It might be thought that serious local action would take place through the tubes connected to the common supply of the electrolyte on the one hand and to the common waste on the other. There is, of course, a potential difference between the tubes of one cell and those of another, but this is localised by the ebonite unions and rubber washers used for coupling up the pipe work, and so far as could be seen no corrosion of the tubes took place during the six weeks this particular battery of four cells was under test. As to how many cells could be coupled up in this way without giving trouble through local currents it is difficult to say.

Some rough experiments were made to see if the local action was greater per cell in this 4-cell battery than in a single cell, the electrolyte

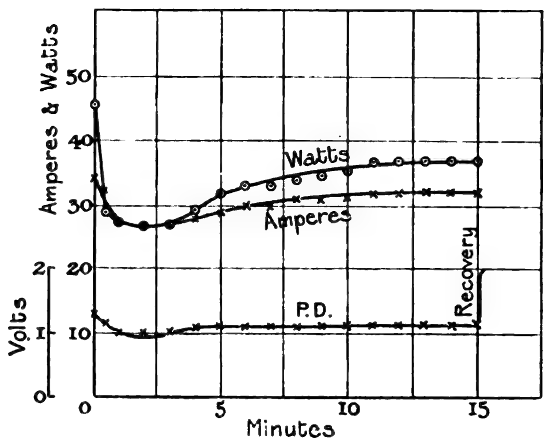


FIG. 7.—Heavy Current Test on Constant Resistance.

Initial current, 35 amperes. Type "A" cell. Solution "P."

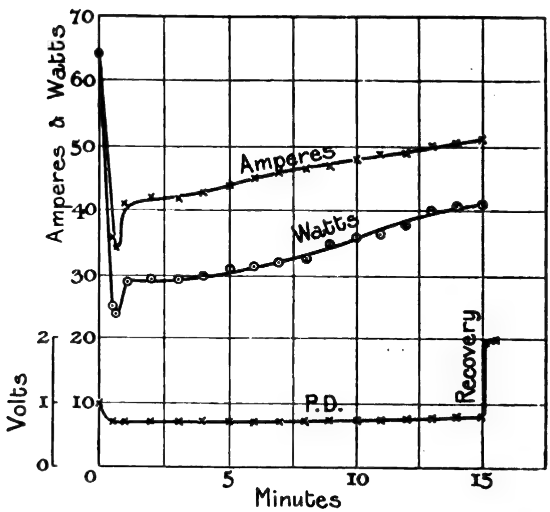


FIG. 8.—Heavy Current Test on Constant Resistance.

Initial current, 64 amperes. Type "A" cell. Solution "P."

being allowed to flow very slowly. So far as the experiments went they tended to show no increase of local action in the battery as compared

with the single cell, but in order to arrive at a conclusive result it would be necessary to work with zincs as far as possible identical, with the flow the same in all cases and with some assurance that the flow of each of the battery cells is the same.

Internal Resistance and Polarisation.—It is difficult to separate these two quantities with certainty, and no attempt has been made to do so. Fig. 6 shows how the terminal pressure and terminal watts vary as the current is increased. The currents were not taken momentarily from the cell, but the external resistance was decreased step by step as

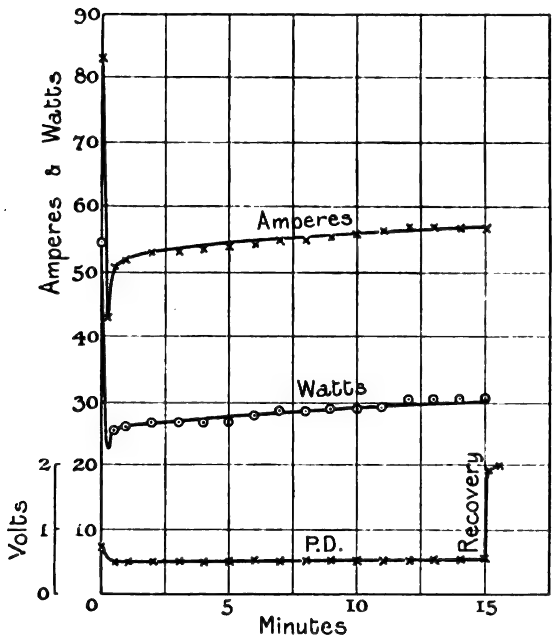


FIG. 9.—Heavy Current Test on Constant Resistance.

Initial current, 83 amperes. Type "A" cell. Solution "P."

quickly as the readings could be taken, and therefore polarisation no doubt reduced the higher current readings to some extent. The highest outputs shown would not be maintained for any long periods, as the cell is overloaded. This test was made with solution L.

The tests shown in Figs. 7, 8, and 9 were made with a similar single cell, using the stronger solution P at a head (between the bottom of the tank and the top of the overflow tube) of 45¾ in., which gave a flow of about 1·9 litres per hour. In each of these tests the external resistance was maintained constant, and the fall of current

was observed for 15 minutes. The current might have been maintained longer, but the cell became very hot with such heavy discharges.

Short-circuit tests with the L solution showed momentary currents of 100 amperes at a terminal voltage of 0·5 to 0·6 volt, the current falling to 80 amperes at the end of 5 seconds. With the stronger P solution momentary currents of 200 amperes were taken at a terminal pressure of 0·5 to 0·55 volt. It follows, therefore, that the internal resistance is well below 0·01 ohm, an extremely low figure. This result is no doubt due largely to the excellent contact between the lead shell and the carbon, both at the top and at the bottom.

Specific Output.—It is a little difficult to compare the output of a Benkö cell with that of accumulators or other cells, because a tank

TABLE II.

Current Output per Square Foot of Plate.

Cell.	Current per Square Foot of Zinc, taking each Side.	Maximum Current Continuously per Cell.
Benkö, A type, solution L	56 (6 amperes per square decimetre)	16 amperes.
Benkö, A type, solution P	90 (10 amperes per square decimetre)	27 "
Lead accumulator (stationary type)	5 to 6 amperes per square foot of positive plate (8-hour rate)	—
Lead accumulator (stationary type)	25 amperes per square foot of positive plate (1-hour rate)	—

is necessary for containing the electrolyte. If this is omitted from the calculation the Benkö cell is placed in a rather unduly advantageous position. On the other hand, it is difficult to fix on any particular size of tank because this will vary with the rate at which the cell is worked for a given time. We might, for example, take a tank having a capacity of 4 to 6 litres for an 8-hour run, but this would not be altogether fair, because a cell with such a tank could run for any length of time, if replenished at intervals, until the zinc had been consumed. Also if it is merely a question of a 1-hour run the tank would be much smaller. I feel, therefore, that a definite basis can only be obtained by disregarding the reservoir, and the following figures are given on that basis.

The usual method of comparison, namely, the specific output

expressed as watt-hours per pound, cannot be applied in this case because the capacity of the Benkö cell has no particular time limit. We are therefore restricted to a comparison on the basis of power in watts per pound. There is also the question of the maximum current obtainable continuously.

TABLE III.

Power per Pound of Cell.

Cell.	Watts per Lb.
Benkö, A type, solution L ...	2·4 (continuously)
Benkö, A type, solution P ...	4 (continuously)
Lead accumulators (automobile cells)...	2¼ (5-hour rate)
Lead accumulators (stationary, in glass boxes)	¼ (8-hour rate) 1 (3-hour rate)

Dealing with this last point first and taking 1·5 volts per cell as the minimum terminal voltage for continuous working, we have the results given in Table II.

From this it appears that the current output of the Benkö cell is

TABLE IV.

Power per Unit Volume.

Cell.	Watts per Cubic Foot.
Benkö, A type, solution L ...	400 (continuously)
Benkö, A type, solution P ...	670 (continuously)
Lead accumulators (automobile cells)...	400 (5-hour rate)
Lead accumulators (stationary, in glass boxes)	120 (3-hour rate) 60 (8-hour rate)

much higher than the current output of the central station type of lead cell, even at the 1-hour rate. This is due partly to the low value of the internal resistance, which permits high currents to be taken, and partly to the fact that there is no delicacy of active material (as in accumulators) to be considered.

Coming to the weight basis of comparison, the weight of the Benkö cell supplied to me was about 10 lbs. per cell, including casing, the electrolyte in the cell and the zinc, but excluding pipe connections. Taking again 1·5 volts per cell as the minimum terminal voltage we have the results given in Table III., which shows that the power as compared with lead accumulators is high.

Another basis of comparison is that of power per unit volume. From Table IV. it will be seen that the Benkö cell again stands very well compared with accumulators.

At high rates of discharge the figures for accumulators become more favourable, but the Benkö cell also is capable of higher rates for short intervals, and it has the great advantage that short circuits do no harm. The above figures are not given with the idea that accumulators will be promptly superseded, but to show the capabilities of the Benkö cell as compared with cells that are well known.

Applications.

I do not propose to discuss all the possible applications of a battery of this kind, but I will refer to a few of the most important.

Laboratory and Miscellaneous Uses.—The requirements of the laboratory will at once come to mind, particularly to those readers who have had the misfortune, like myself, to depend upon primary batteries in experimental work, especially if any considerable current is required of a steady value. Moreover, the preparation of a primary battery for an efficient life of such short duration is always irksome and generally involves "mess." Even if accumulators are available, they require careful supervision. The Benkö cell has the advantage that it is small, easy to handle, and requires no careful attention. When it is not required it can be left on one side without fear of deterioration, the only desirable precaution being the running of some water through it to free it from the used electrolyte after heavy work. Since laboratory requirements are very varied, heavy currents being required at times, it is desirable to work with a voltmeter across the terminals so as to see at a glance if the battery is being overloaded. It may be mentioned that if the strength of the electrolyte is varied, some considerable time (say, half an hour) elapses before the full effect of the change is felt. If a cell refuses to take its normal load through improper using, a thorough wash-through by allowing water to flow through the cell, followed by electrolyte, the current being then raised gradually to the desired value, will set matters right.

The charging of ignition cells, electro-plating on a small scale, and possibly submarines (owing to the peculiar conditions involved) are fields in which such a battery would prove useful. There is also the electric lighting of yachts having no generating plant. At present this is sometimes effected by means of accumulators which are taken ashore for charging as opportunities may arise. Such a method

however, has obvious drawbacks and limitations, and a convenient primary battery would, no doubt, be welcomed as a substitute.

The electric miner's lamp has made but small progress in this country, although both accumulators and primary cells have been tried. For this work a lamp has been designed in which the Benkö cell used is very small and the electrolyte is under pressure. Possibly this design may prove a solution to the problem, but I am unable to speak from experience on this point.

Telegraphy. — Although accumulators are being employed increasingly in telegraphy owing to their small internal resistance there are many cases in which they cannot be so applied, and therefore large numbers of primary cells are still in use for telegraphic work. Among these, bichromate cells of the quart and three-pint sizes figure largely and involve a good deal of cost and work in their maintenance.

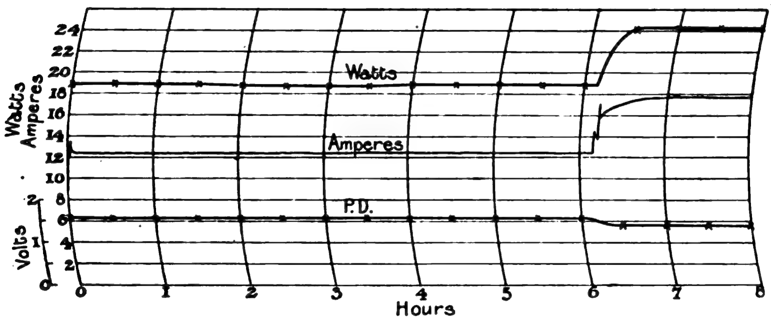


FIG. 10.—Discharge Curves of Benkö Cell.

Type "A." Solution "L."

In order to show the capabilities of the Benkö and ordinary bichromate cells (without porous pot), the curves in Figs. 10, 11, and 12 are given. Fig. 10 shows the record taken by a recording ammeter of the discharge of an A type Benkö cell along with plotted curves of terminal pressure and terminal watts. It is seen that a remarkably constant current of over 12 amperes was taken from the Benkö cell for six hours and the current was then increased to over 17 amperes for about two hours. The latter part of the discharge took a little time to become steady, due no doubt to the additional heating of the cell.

The bichromate cell used for comparison held three pints of the same electrolyte and had one zinc plate and two carbons; all three plates were 6¼ in. wide and were immersed to a depth of 7¾ in. It will be noted that the area of the zinc was more than double that of the Benkö cell, and the carbon surface also much greater (though a little less in proportion). Yet when this cell was switched on to the same

circuit as that which carried 12 amperes in the test just referred to, the current, which rose momentarily to 9·6 amperes, fell quickly below 8 amperes, and continued to fall as shown in Fig. 11. The potential difference and watts also fell rapidly. Even when a circuit of higher resistance was used, giving an initial current of 6 amperes, the current fell off after a couple of hours, as seen in Fig. 12. It is this characteristic which is so annoying to users of the ordinary primary battery, but which is so completely eliminated by the Benkö cell.

Since the currents used in telegraphy run merely to some milli-amperes, it will be seen that Benkö cells very much smaller than the type A (for example, less than a quarter that size) would give the necessary current for telegraphic work. Such cells have been made, and they present the advantage of occupying a much smaller space than the usual primary cells, and, moreover, are equivalent to the accumulator in constancy of E.M.F. and low value of internal resist-

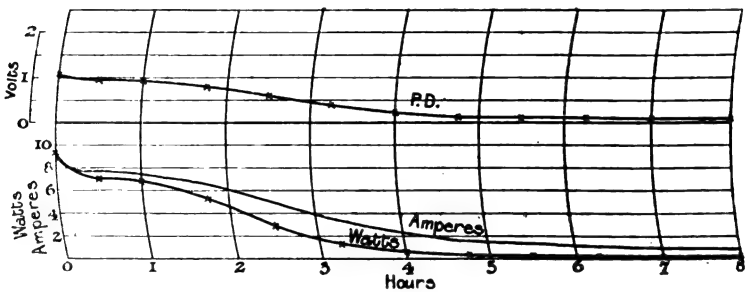


FIG. 11.—Discharge Curves of 3-pint Bichromate Cell, on same Circuit as in Fig. 10.

Solution "L."

ance. Obviously also they would be much simpler to keep in order than a battery of ordinary bichromate cells.*

Country House Lighting.—In the applications so far discussed, the cost of energy is not of paramount importance, but I wish to refer now to a field where the cost must be taken into account. Country houses above a certain size can be supplied very efficiently with electric light by the usual type of private plant. But if the house is below a certain size (for example, one requiring fifty 10-c.p. lamps), an oil engine set, with its attendant accessories, presents very marked disadvantages.

* For work of this kind the flow need only be very slow. Since this paper was written a type of Benkö cell has been developed in which the compartment outside the carbon is filled with very strong electrolyte and the inner compartment is merely filled with water; circulation of the electrolyte then takes place by diffusion, there being no supply and waste pipes, or pressure reservoir. Probably cells of this kind will be the most suitable for telegraphy and for miners' lamps where only small currents are required.

These disadvantages are chiefly due to the fact that such plant is expensive and involves the running of machinery which must receive a certain amount of skilled attention. The skill is often acquired by the gardener, or other handy man, but in many of the smaller country houses, particularly if unoccupied for a good many months in the year, it may be felt that even this rough skill cannot be conveniently supplied. During the last few years the use of the low-voltage metal filament lamp has very materially modified the position, reducing the necessary outlay; but even so there are many people who hesitate to spend money on such a plant to light a house of the size mentioned. All who have been concerned in this class of work are well aware that there are any number of country houses where electric light would be welcomed but for these difficulties.

Let us take the case of a house requiring fifty 10-c.p. metal lamps. A pressure of 25 volts would be adopted, and as the house would not

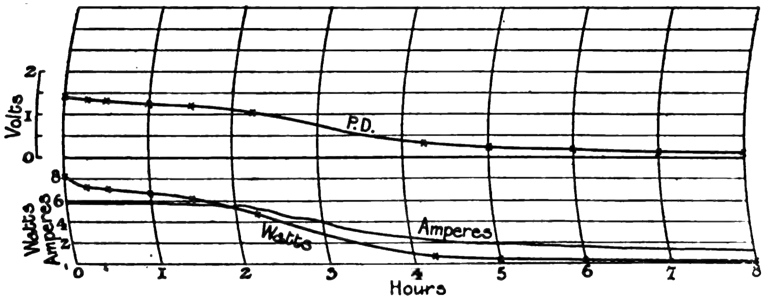


FIG. 12.—Discharge Curves of 3-pint Bichromate Cell on Higher Resistance, to give 6 Amperes Initially.

Solution "L."

be wired throughout, we may assume that a large proportion, say, 75 per cent. as a maximum, would be in use at one time, and would require a current of 15 amperes. A battery of accumulators would be necessary and the generator would have to give an output of about 1·5 k.w. In order to avoid nuisance from noise and smell it is necessary to put down the plant at some distance from the house and to lay an underground cable, which is a considerable item in the cost. As a rule also a special building has to be erected. A complete installation of this kind, excluding the house wiring, will cost, roughly, about £200.

The cost of merely running such a plant is comparatively small, as the paraffin, oil, waste, etc., amounts to very little. But if interest on the outlay is taken at 5 per cent., depreciation and repairs at 7½ per cent., and labour only at one hour per day, or 300 hours at 6d., the total cost is considerable, and for 400 units per annum would amount to about 1s. 10d. per unit. Of course the high price is off-set by the

advantages of the light, and thus people are willing to pay accordingly, but the smaller the house the less advantageous is such a plant, and the less the occupier is willing to spend.

We may now take as an alternative a Benkö battery. No special building is necessary. A battery of 16 or 17 cells would give a working pressure of 25 volts, and as the space occupied would be small (say 5 ft. 6 in. × 2 ft. 6 in. × 8 ft. high) accommodation would generally be available, without alteration. By using a pressure tank even this space could be much reduced. There would be no objection to having the battery in the house, as it is free from smell, and thus it would be connected direct to the house wiring without the necessity for underground cable and consequent drop of pressure. The cost would be small, probably in the neighbourhood of £20.

With regard to the cost of running the battery, prices of materials (wholesale) may be taken as follows: Amalgamated zinc plates, about £34 per ton; sodium bichromate, 3d. per lb.; concentrated sulphuric acid, £3 2s. 6d. per ton, or more dilute acid, £1 10s. per ton. At these prices and allowing for local action and waste zinc which is re-sold, I have found that electric energy can be generated continuously with the L solution at a cost of about 2s. per unit, the cost varying with the conditions as mentioned below. This figure is made up approximately as follows on the assumption that the waste zinc would amount to about 25 per cent. and be re-sold at, say, £1 10s. below the market price of raw zinc :—

	Per Unit.
Zinc	10d.
Sodium bichromate	11d.
Sulphuric acid	3d.
	24d.

Cost of carriage would, of course, have to be added for each particular case and also the cost of labour. The latter would be very small if proper facilities were provided, as a solution of the kind used is made very quickly. From what has already been said, a cost of 2s. per unit is not prohibitive, and even 2s. 6d. per unit would not be out of the question. The smaller the house the more favourable is the position of the battery as compared with other plant. There are many small country houses where owners would be prepared to wire a few of the principal rooms, and use, say, 200 units per annum at such a price, for even at 2s. 6d. per unit this would only amount to £25 per annum, which sum would often be gladly paid for the advantages gained. A strong feature of such a battery is that it requires no attention when not in use, and in this respect it is at an advantage as compared with accumulators.

The simplest method of working such a battery is to turn on the flow of electrolyte when the light is required, and the flow would be turned off on retiring at night. This would still permit the use of an

occasional light during the night owing to the quantity of electrolyte in the cells, and it is stated that two or three 10-c.p. lamps could be supplied for the whole night by the battery here considered. Or water may be run in if a water tank is provided, as in Fig. 5, the cells thus acting by diffusion. It would seem, however, that some arrangement for the automatic regulation of the flow of electrolyte would be preferable in many cases, as the cost in practice must depend largely on the way in which the battery is used.

With a uniform flow it follows that if the electrolyte is exhausted to an economical extent with the full load, it will not be properly

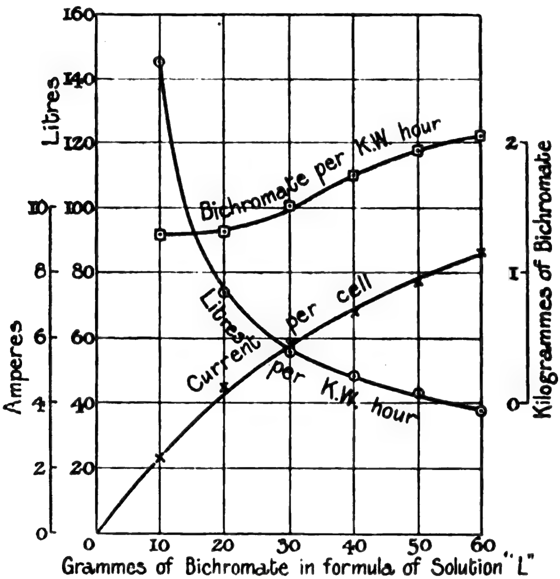


FIG. 13.—Experimental Curves showing Effect of Varying the Quantity of Bichromate in the Solution.

used up at times of light load. To remedy this to some extent the electrolyte after passing through the cells may be mixed with some fresh electrolyte (in the proportion of, say, 3 parts of the former to 1 of the latter) and returned for further use. This "refreshed" solution, however, is not capable of taking so heavy a load as the original solution. For that reason, and having regard also to the fact that the bichromate may easily be the most expensive item in the cost, it may perhaps be preferable to use a solution once with less bichromate rather than a richer solution twice, notwithstanding the fact that the battery will not take such a heavy load. With this point in view I ran a cell with a series of electrolytes differing only in the quantity of sodium bichromate (otherwise it was the L solution); and the current was varied to find the maximum current that could be

supplied continuously at a pressure of 1·5 volts and with a flow of ½ litre per hour. The quantity of bichromate per k.w.-hour was then calculated. The results obtained are shown in the curves of Fig. 13, and it will be noticed that the cost per unit becomes lower as less bichromate is used. Probably also the local action is less. An objection to pursuing this course very far is that, apart from the capacity of the cell being reduced, the quantity of electrolyte to be handled becomes larger. It might, however, be an advantage to use 30 grammes per litre as against 60 grammes in the solution L, saving about 3d. per unit.*

With regard to labour, it may be mentioned that the zincs weigh 1 lb., and if we take 3 lbs. (a high figure to allow for waste and unused zinc) per unit, then a single cell will give ⅓ unit and a battery of 17 cells will give 5⅔ units before the zincs need be changed. If a house is using 1 to 2 units per day this means that the zincs are changed once or twice a week. As the operation is very simple it takes very little time.

From the point of view of labour the electrolyte is more important than the zinc. With a constant output the amount of electrolyte per unit will be, say, 7¾ gallons. If, however, a battery such as we have assumed is allowed to flow steadily at a rate of ½ litre per cell, then a 5-hour run would require 9⅓ gallons. This emphasises the desirability of automatic regulation of the flow. If hand regulation is adopted and not properly applied the amount of solution required might thus be as much as 15 gallons per day in the winter, or say 10 gallons per day if the electrolyte is used twice and "refreshed." On the other hand, with automatic regulation this quantity once or twice a week for 1 to 2 units per week would be enough. With proper arrangements the handling of these quantities would take very little time. These figures emphasise the fact that the cost of running depends largely on the method of running.

As far as can be judged the cost of repairs should be very small, or negligible, and equally the interest on capital is scarcely worth considering. It follows, therefore, that electrical energy can be generated at about 2s. per unit under favourable conditions, and this cost will vary according to the carefulness of the regulation.

From what has been said I think it will be admitted that the Benkö cell provides an electric generator which will be found extremely useful for many purposes, and that it opens up a field in the lighting of small country houses which has hitherto been closed to this form of illumination.

* Since the above was written batteries have been made up combined with accumulators. In such cases the head is reduced to 50 cms. and the flow of electrolyte is cut down to one-fifth litre per hour per cell. A 24-volt battery then consists of 18 Benkö cells in parallel with 12 accumulators, and is stated to be capable of running seventy 16-c.p. lamps for seven hours at a time. In this case the Benkö cells are run more economically as regards the electrolyte and at a reduced output of 8 to 10 watts per cell

INDEX TO VOL. 46.

1911.

EXPLANATION OF ABBREVIATIONS.

[P] signifies a reference to the general title or subject of a Paper.

[*p*] signifies a reference to a subject incidentally introduced into a Paper.

[D] signifies a reference to remarks made in a Discussion upon a Paper, of which the general title or subject is quoted.

[*d*] signifies a reference to remarks incidentally introduced into a Discussion on a Paper.

Note.—The lists of speakers in the Discussion upon any Paper will be found in the Table of Contents at the beginning of the volume.

A.

B.

C.

D.

E.

F.

G.

H.

I.

J.

K.

L.

M.

S.

T.

V.

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No. 207. MAY, 1911. VOL. 46.

JOURNAL

OF THE

INSTITUTION OF ELECTRICAL ENGINEERS,

ORIGINALLY

THE SOCIETY OF TELEGRAPH ENGINEERS.

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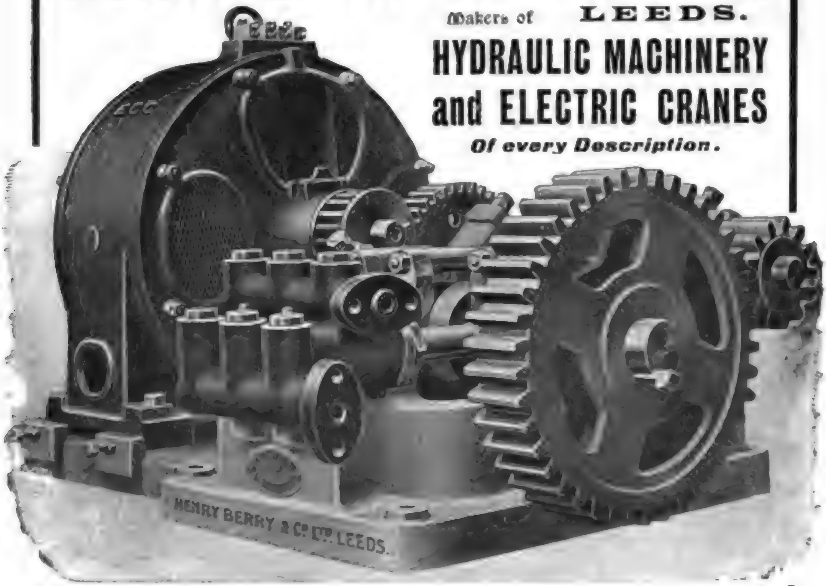
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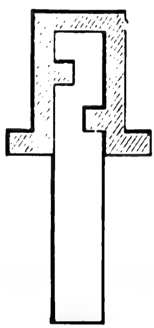

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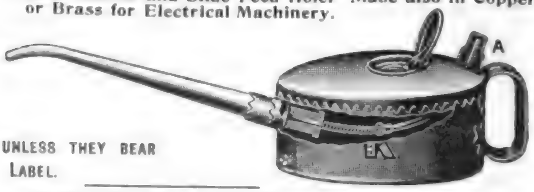

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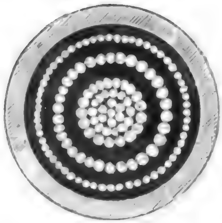

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